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Evaluating Substrate Metrics for Monitoring Sediment Impairment of East Tennessee Streams.

James Hunter Terrell
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To the Graduate Council:

I am submitting herewith a thesis written by James Hunter Terrell entitled "Evaluating Substrate Metrics for Monitoring Sediment Impairment of East Tennessee Streams.." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

Carol P. Harden, Major Professor

We have read this thesis and recommend its acceptance:

John S. Schwartz, Liem T. Tran

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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A Thesis Presented for the

Master of Science

Degree

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James Hunter Terrell

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ABSTRACT

Section 303(d) of the Clean Water Act (CWA) requires states to assess and list all streams that do not meet water quality criteria for their designated use classes. In Tennessee, the Tennessee Department of Environment and Conservation (TDEC) uses macroinvertebrate surveys to assess the condition of streams designated for "fish and aquatic life" and the progress of targeted waterbodies toward meeting established standards for sediment. As of yet, no substrate metric has been established to monitor water quality or to document progress toward water quality improvement with respect to fish and aquatic life in Tennessee. A substrate metric that could be efficiently measured and would represent the needs of aquatic species would be valuable for monitoring streams with known sediment impairment to detect water quality improvement. The objectives of this study were to (1) investigate the relationships between riffle substrates and benthic macroinvertebrate data, provided by TDEC; (2) assess the potential use of substrate metrics as a monitoring tool for benthic habitat status; and (3) examine variation in riffle substrates over time in the Ridge and Valley Ecoregion of Tennessee. Bed and interstitial sediment were characterized at sites corresponding with TDEC macroinvertebrate sampling stations. Bed sediment characteristics were significantly correlated with benthic macroinvertebrate data; however, interstitial fines yielded no significant correlations with benthic macroinvertebrate data. Substrate metrics did not differ significantly between varying levels of impairment; however, they did differ significantly when all impaired sites were combined into a single impairment group. The lack of significant differences between varying classes of reach impairment suggests that substrate metrics may not be able to distinguish impairment at the level necessary for monitoring impairment. However, substrate metrics may be of potential use in monitoring sites where impairment is less ambiguous. To investigate change in riffle substrate over time, three sites were monitored over the course of a year. Preliminary observations showed little change in riffle substrate during the study period, suggesting that seasonal restrictions on substrate surveys are unneccessary.

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CHAPTER ONE

1 INTRODUCTION

1.1 BACKGROUND AND JUSTIFICATION

Human disturbance has a long history of affecting water quality and the diverse biota within affected streams (Maloney et al. 2008). Within the past 40 years, the U.S. government has passed legislation to protect streams, particularly from point sources such as industrial outfalls or municipal waste facilities. In the 1980s, scientists, legislators, and conservationists began to address the problem of nonpoint source pollution within the watersheds of the U.S (EPA 2008).

Section 303(d) of the Clean Water Act (CWA) mandates states to assess and list all streams that do not meet water quality criteria for their designated use classes. Streams determined to be non-supporting are considered "impaired," and a Total Maximum Daily Load (TMDL) of the particular pollutant must be developed for targeted waterbodies. Once TMDLs are established, pollutant sources must be identified and controls implemented to reduce the amount of pollutant to a level that meets water quality criteria. States are then required to monitor targeted waterbodies to assess whether they are within the range defined by the TMDL for that particular pollutant.

Currently, in Tennessee, the Tennessee Department of Environment and Conservation (TDEC) uses macroinvertebrate surveys to assess the impairment of streams designated for "fish and aquatic life" and the progress of targeted waterbodies toward meeting established standards for sediment with macroinvertebrate surveys. Results from these surveys are then compared to established biocriteria to determine whether waterbodies meet water quality standards for fish and aquatic life. This method is well tested and presents a detailed biological assessment of streams; however, it can be expensive and time consuming.

As of yet, no substrate metric has been established to monitor water quality or to document progress of TMDLs toward water quality improvement that would affectfish and aquatic life in Tennessee. A substrate metric that is efficiently measured and represents the needs of aquatic organisms could prove to be a valuable tool in implementing and monitoring efforts to improve water quality in streams, especially those impaired by an excess of fine sediment. This thesis was designed to assess the potential use of substrate metrics by examining the relationships between substrate metrics and benthic habitat status, as determined by macroinvertebrate surveys, in wadeable streams of the Ridge and Valley ecoregion in East Tennessee. Findings from this study could help TDEC assess the potential use of physical habitat metrics in monitoring water quality.

1.2 The Clean Water Act, TMDLs, and Determining Impairment in Tennessee Streams

1.2.1 The Clean Water Act

The 1948 Federal Water Pollution Control Act was the first piece of legislation to address water pollution in the U.S. Through a series of reorganizations and additional amendments in 1972 and 1977, the legislation came to be commonly known as the Clean Water Act (CWA) (EPA 2011). Initially, the CWA focused on point-source pollution, e.g., wastewater or industrial discharges, and maintaining the chemical integrity of waterbodies. However, with the passage of the 1977 amendments, the CWA recognized the need to address nonpoint source pollution. The 1980s saw a significant increase in efforts to reduce nonpoint source pollution through voluntary programs with landowners and by regulating stormwater discharge from municipalities (EPA 2008).

Water quality standards (WQS) are the tools within the CWA that attempt to translate the broad goals of the CWA into waterbody-specific objectives for all waterbodies determined to be waters of the Unites States (EPA 2008). The WQS program essentially breaks down into three components—designated uses, water quality criteria, and antidegradation policies.

The Designated Use of a waterbody states the primary use of that particular waterbody and, in turn, determines what Water Quality Criteria (WQC) it is required to meet. WQC provide values that, if obtained, will protect the designated use of a waterbody. Criteria can be numeric or narrative, but must be representative of the designated use and scientifically based. Numeric criteria express the condition of the waterbody given certain measures, such as dissolved oxygen (DO) or heavy metals. Narrative criteria consist of narrative statements such as "free from..." or a description of the aquatic community. Assessments of waterbodies designated for fish and aquatic life use narrative biological criteria.

Once criteria are set, states are required to monitor and determine the status of waterbodies within their boundaries. Waterbodies meeting criteria are considered to be "supporting" of their designated uses and those not meeting criteria are considered to be “not-supporting.” States report their findings to EPA in an integrated report that combines the 305(b) report, traditionally reporting the status of all waters, and the 303(d) report, traditionally reporting only those waters considered threatened or impaired. Of particular interest to this study is the 303(d) list.

1.2.2 Total Maximum Daily Loads

Once a waterbody is determined to be impaired and has been listed on the 303(d) list, a Total Maximum Daily Load (TMDL) of the particular pollutant(s) of interest must be established. By definition, the TMDL is the amount of a particular pollutant(s) that a waterbody can receive and still meet water quality criteria (EPA 2005). Constituent elements of a TMDL are described in the following equation:

$$Wasteload\ Allocation + Load\ Allocation + \{Margin\ of\ Safety\} = TMDL$$

Wasteload refers to all point source loads, load is a combination of all nonpoint source and background loads, and the Margin of Safety is designed to account for uncertainty in TMDL calculations (Dilks and Freedman 2004). However, a TMDL is more than just an equation for determining loading in a system. It is a process that presents states with a method for “weighing multiple competing concerns and developing an integrated pollution reduction strategy” ,while involving all stakeholders within a watershed (EPA 2010). Key components of a TMDL include identifying the problem, which presents background information and describes the nature of the impairment; identifying appropriate water quality indicators; assessing the source of pollutants in the watershed; linking water quality targets to sources; allocating sources; and monitoring to evaluate progress toward the TMDL targets.

1.2.3 Determining Impairment of Fish and Aquatic Life in Tennessee

Tennessee Department of Environment and Conservation (TDEC) uses narrative biological criteria, based on the Rapid Bioassessment Protocols developed by EPA (Barbour et al. 1999), for initial assessments of waterbodies for listing on the 303d list, as well as for monitoring TMDL targets for waterbodies designated for fish and aquatic life (TDEC 2006). Attainment of criteria is determined using biological surveys of macroinvertebrates, which characterize stream reaches using a multimetric index of biotic integrity that reflects different aspects of stream biology (Kerans and Karr 1994). Attributes of the index include characteristics such as taxonomic richness of the sample, total number of genera of *Ephemeroptera, Plecoptera, and Trichoptera* (mayflies, stoneflies, and caddis flies, respectively), and percentage of sample consisting of species tolerant to higher concentration of nutrients (TDEC 2006). Macroinvertebrate assemblages prove to be a good indicator of localized conditions due to their limited migration patterns and sessile modes of life (Barbour et al. 1999). Additionally, macroinvertebrates are often diverse in small streams where other biological indicators, such as fish, are limited and may not be representative of conditions in the stream (Barbour et al. 1999). However, it is important to recognize that this type of index is a composite and is sensitive to multiple stressors.

In the field, TDEC uses two methods of biological survey, biorecons and semi-quantitative single habitat surveys (SQSH), to determine the biological integrity of stream reaches and, in turn, a stream's impairment. Biorecons are used for general watershed assessments or when attainment status is obviously "supporting" or "non-supporting." SQSHs are more thorough assessments of the biological community and are considered more scientifically defensible (TDEC 2006). The SQSH sampling procedure is outlined in TDEC's standard operating procedure for macroinvertebrates (TDEC 2006).

1.3 In-channel Sediment and Impacts on Aquatic Insects

1.3.1 Sediment Processes and Pollutants

Sedimentation in streams is a complex, dynamic process that is key to forming the valley, the channel, and the aquatic habitat within the channel. Sediment in the channel originates from uplands, where denudation processes weather, break down, entrain, and transport particles downslope until they deposit on a surface (Leopold et al. 1964). Sediment in a stream originates from upslope processes and from within the channel itself, as banks are eroded or upstream depositional features are transported downstream. The structure of a channel is a function of watershed characteristics. The quantity and nature of sediment flowing through a channel, the characteristics of the channel bed and banks, and the discharge patterns of the stream all affect the formation of a channel (Leopold et al. 1964). In a stable system, the form and local gradient of the channel fluctuate, deviating around standard conditions. This type of stream is defined as a stable or "graded" stream. Although the stream may meander across valley floors, entraining and depositing upland sediment, the average condition of the channel and sediment transport remains the same (Gordon et al. 2004).

Sedimentation is a natural process; however, excessive amounts of inorganic sediment in a channel can degrade aquatic habitats, thereby becoming a pollutant.

Sediment pollution is often a function of disturbance in the watershed that leads to a change in channel conditions. Since the channel represents a balance of deposition and transport, a change in any of the factors forming it can create an unstable system (Leopold et al. 1964). One potential effect of an unstable channel is increased deposition of fine sediments. If the supply of fine sediments to a channel is greater than that which the channel can transport, deposition occurs. As a result, habitats become increasingly homogenous, which negatively affects the composition of aquatic communities (Henley et al. 2000).

In the U.S., over 1 million km (~620,000 miles) of stream are reported to be in "poor" condition (Faustini et al. 2009). Of these, 25% are impaired by riparian disturbance or an excessive of fine sediments. In Tennessee, over 9,000 km (6000 miles) are reported to be impaired by silt (TDEC 2010). Typically, sediment pollution is associated with land-use practices such as logging, mining, agriculture, and urban development. Streambank erosion can also contribute considerable amounts of fine sediments when increased discharge exacerbates natural erosional processes (Waters 1995).

1.3.2 Impacts of Sediment Pollution on Aquatic Insects

The effect of increased fine sediment on aquatic insects has been well documented in the literature. As pointed out by Lemly (1982), early studies documented the effects of mass deposition events and the deleterious effects to aquatic communities; but, until the 1980s, very little research had focused on the effect of incremental increases in fines and sands in interstitial spaces between gravels. Since then, a large literature has been established that documents the sources and effects of fine sediments on aquatic insect communities.

Increased sedimentation on the channel has deleterious effects on aquatic insect assemblages by way of reducing available habitat (Lenat et al. 1981), increasing fines in the hyporheos (Richards and Bacon 1994), clogging gills (Lemley 1982), and increasing drift (Culp et al. 1986). Henley et al. (2000) presented a thorough review of effects of fine sediment on aquatic communities. Response of aquatic insect assemblages to sediment has been documented in several studies. In a field experiment with in-situ trays embedded in the substrate, Angradi (1999) found that *Ephemeroptera, Plecoptera, and Trichoptera* (EPT) taxa richness responded negatively to artificial increases in fine sediments. Kallar and Hartman (2004) characterized substrate and macroinvertebrate communities at seven sites with varying amounts of fine sediments. They found a consistent negative relationship between fine substrate particles (< 0.025 mm) and EPT taxa richness. More specifically, results suggested that a fine sediment threshold existed, such that EPT taxa were negatively affected when fine sediments (0.25 mm) were greater than 0.8–0.9% of the substrate composition. Using in-situ boxes in a stream, Richards and Bacon (1994) examined sediment in the hyperheos and determined that the presence of fine sediments smaller than 1.5 mm played a role, although secondary to stream size, in controlling macroinvertebrate assemblages.

1.3.3 Substrate Metrics

Common measures of substrate in studies analyzing the impact of sedimentation on macroinvertebrate communities include both quantitative and qualitative metrics.

Quantitative metrics are usually derived from Wolman pebble counts (Wolman 1954), reported as D_{50}, the median particle diameter of the pebble count. Pebble counts consist of sampling and measuring the intermediate axis of 100 particles from the streambed and calculating a particle-size distribution of substrate on the streambed. A qualitative metric of particular interest to this study is embeddedness. Embeddedness, as defined by Platts et al. (1983), is the "degree that larger particles (boulder, rubble, or gravel) are surrounded or covered by fine sediment." Several other authors have variously defined the term; however, all definitions relate either to a quantity of fines in stream substrates, expressed as the percentage of the stream's surface area covered by fines, or the depth to which coarse substrates are surrounded by fines (Sylte 2002).

Several methods for determining embeddedness of the channel bed exist and are used by different agencies. Of particular interest for this study is the USEPA EMAP method. This method averages cross-sections of an entire reach into a single embeddedness value that is thought to be more representative of the entire reach. Sennatt et al. (2006) used multiple embeddedness methods in tributaries of the Connecticut River and concluded that the EMAP method was able to track expected changes in embeddedness downstream of a dam. Additionally, Faustini et al. (2009) reported that the EMAP protocol was able to detect trends in the proportion of streambed covered by fine sediments, which could potentially be used to detect change in aquatic habitat quality caused by changes in land use.

Some questions have been raised about the suitability of embeddedness as a substrate-monitoring tool (Potyondy and Sylte 2008, Sennatt et al. 2008). Although used by USDA Forest Service in the 1980s and 1990s, embeddedness has been replaced by other methods, such as pebble counts, that are more quantitative (Potyondy and Sylte 2008). However, Sennatt et al. (2006) offered the argument that solely using Wolman pebble counts to quantify substrate particles has been shown to bias results towards larger substrate sizes (> 15 mm), in turn, underestimating fine particles that play a central role in the concept of embeddedness.

1.4 Research Objectives

The objectives of this study were to investigate the relationships between riffle substrates and benthic macroinvertebrate data, provided by TDEC, and to assess the potential use of substrate metrics as a monitoring tool for benthic habitat status in the Ridge and Valley Ecoregion of Tennessee. The underlying conceptual framework for this research is that the status of benthic habitat is related to the size and distribution of substrate on the channel bed and, in turn, can be monitored using substrate metrics. Specifically, I expected to see a decline in benthic habitat status and a decrease in median particle diameter with an increase in embeddedness. I also expected to see a decline in benthic habitat status with an increase in the concentration of fine sediments in interstitial spaces. I examined variation in bed sediment characteristics over time at three monitoring sites within the ecoregion. I hypothesized that:

1. Macroinvertebrate survey scores would be negatively correlated with amount of fines within the riffle, quantified using the percent of particles in sample less than 2 mm and by embeddedness metrics.

2. Macroinvertebrate survey scores would be positively correlated with median particle size (D_{50}) values.
3. Embeddedness values would be negatively correlated with D_{84}, D_{50}, D_{16} values, and positively correlated with the percent of sample less than 2 mm.
4. Substrate metrics would differ significantly between non-impaired and impaired sites.
5. Using logistic regression, substrate metrics can be used to predict impairment in stream reaches.
6. Concentrations of fine sediments in interstitial spaces would be negatively correlated with macroinvertebrate survey scores.
7. Substrate metrics would show variation over time.

1.5 Organization of Thesis

This thesis is divided into five chapters. The first chapter justifies my research and puts it in the context of regulations pertaining to the Clean Water Act. Furthermore, the first chapter reviews relevant literature and presents the objectives and specific hypotheses of the study. Chapter Two describes the study area and the field, lab, and statistical methods used in the study. Chapter Three presents results from the study. In Chapter Four, I discuss the results of the study and, in Chapter Five, present major conclusions and detail future research needs.

Chapter Two

2 Methods

2.1 Study Area

2.1.1 Physiography, Geology, Climate, and Vegetation

The Ridge and Valley ecoregion (67) stretches from southeast New York to northeast Alabama, approximately 1,600 km (995 miles). Roughly parallel ridges and lowland valleys running northeast to southwest characterize much of the region. The geology of the Ridge and Valley was formed by the Alleghenian Orogeny occurring approximately 248 million years ago; however, the topography of the region today is a result of weathering, mass wasting, and erosion that began at the conclusion of the Alleghenian Orogeny and presently continues (Abramson and Haskell 2006). Parallel folds have been sculpted into parallel ridges and valleys by differential weathering. Differential weathering first breaks down softer rocks, such as shale and limestone, while leaving harder rocks like sandstone and other conglomerates. As a result, the breakdown of less resistant rocks forms valleys and harder rocks remain as ridges (Abramson and Haskell 2006).

In Tennessee, the Ridge and Valley is a 60–90 km wide belt predominately located in the eastern portion of the state between the Cumberland Plateau (68) and Cumberland Mountains (69) ecoregions to the west, and the Blue Ridge ecoregion (66) to the east. Elevations of ridges vary widely from 300 to 750 m, and valley floors average near 200 m in Southern areas of the state and near 300 m closer to Virginia (Etnier and Starnes 1993). The region is mostly underlain by dolomite, limestone, shale, and sandstone formations that have undergone extreme folding and faulting with rocks ranging in age from Cambrian to Mississippian (USDA 1981).

The Ridge and Valley is subdivided into four Level 4 ecoregions in Tennessee: Southern Limestone/Dolomite Valleys and Rolling Hills (67f), Shale Valleys (67g), Southern Sandstone Ridges (67h), and the Southern Dissected Ridges and Knobs (67i) (Griffith et al. 1987). Natural vegetation within all sub-ecoregions consists of Appalachian Oak Forests, with mixed oaks, hickory, pine, poplar, birch, and maple. Mixed mesophytic forests are known from all sub-ecoregions, with the exception of the Southern Shale Valleys. Southern Limestone/Dolomite Valleys and Rolling Hills (67f) also have bottomland oak forests and cedar barrens (Griffith et al. 1987). Typical land use in the region consists of cropland, pasture, deciduous forests, and rural development, as well as urban development near city centers such as Knoxville, Chattanooga, and the Tri-Cities.

The Ridge and Valley ecoregion in East Tennessee is located in the humid subtropical climate zone (Koppen classification unit Cfa). The area is affected by both dry continental air masses from the northwest and moist air masses originating in the Gulf of Mexico. Annual precipitation averages 134 cm, with highest amounts falling from April through October. Temperatures are typically lowest in the months of December through February and highest from June to August. Average minimum and maximum temperatures near Knoxville averaged 8^{o} C and 20^{o} C between 1966 and 2010 (SERRCC 2011).

2.1.2 River Basins and Stream Geomorphology

The Tennessee River and its tributaries drain most of the ecoregion in Tennessee. Formed by the confluence of the Holston and French Broad rivers, the Tennessee River has been modified with a series of impoundments, as have many of its larger tributaries, and is currently regulated by the Tennessee Valley Authority for navigation, flood control, and hydropower. Major tributaries to the Tennessee River flowing through the Ridge and Valley Ecoregion include the Clinch, Holston, Powell, and Watauga rivers in the northeast; the French Broad, Little, Pigeon, and Little Tennessee rivers in the east, and the Ocoee and Hiawassee rivers in the southeast. The Conasauga River, a tributary to the Coosa River and greater Mobile basin, drains one small portion of the Ridge and Valley in the southeastern part of the state.

Larger streams and rivers, mostly structurally controlled by ridges running northeast to southwest, meander through parallel valley floors and are fed by smaller tributaries bisecting ridges. Substrates mainly consist of limestone rubble and bedrock in riffles, and silt and sand in pools. Larger rivers have extensive sand and gravel shoals (Etnier and Starnes 1993). A 2005 TDEC study characterized stream geomorphology based on reference reaches in each sub-ecoregion. Cross-section types include sloped, broad U-shaped, and U-shaped with high banks when streams are gullied. Streams in all sub-ecoregions have typically low to moderate gradient, with slopes of less than 4%. Substrates consist of either bedrock or gravel in all sub-ecoregions (TDEC 2005).

2.2 Site Selection

In this study, sample sites were paired with established TDEC sampling stations within the Ridge and Valley ecoregion. Since the SQSH method is more robust and scientifically defensible (TDEC 2006), sites were limited to stations where these data were available. Using the TDEC database of sampling stations and through collaboration with TDEC, a total of 30 sites were selected based on the following criteria:

- Site is located within the Ridge and Valley Ecoregion (67),
- Macroinvertebrate data had been collected within the last 3 years (≥2007),
- The upstream contributing area is not urbanized,
- The site is not downstream of a point source nutrient input (e.g., wastewater treatment discharge).

Originally, sites within the Little River watershed were given preference due to the abundant water-quality, land-use, and sediment data available for comparison (TVA 2003, Hart 2006, Burley 2008, Harden et al. 2009, and Foster 2010). To increase the sample size, sites outside of the Little River watershed were chosen based on the same criteria. I intended to survey sites from a broad distribution of TMI scores by sampling high, medium, and low scoring streams. However, since SQSH surveys are not necessarily performed on "obviously impaired" streams

(TDEC 2006), no sites with low TMI scores were sampled. A map of all sites can be found in Figure 1. Site locations and coordinates are listed in Table 1.

Site IDs used in this study are the same as those used by TDEC. The first five characters are an abbreviation of the stream name, the following four numbers are the river or creek mile, and the last two characters are an abbreviation of the county name. For example, the site ID NAILS000.8BT would correspond to a site located on Nails Creek, at creek mile 000.8, in Blount County.

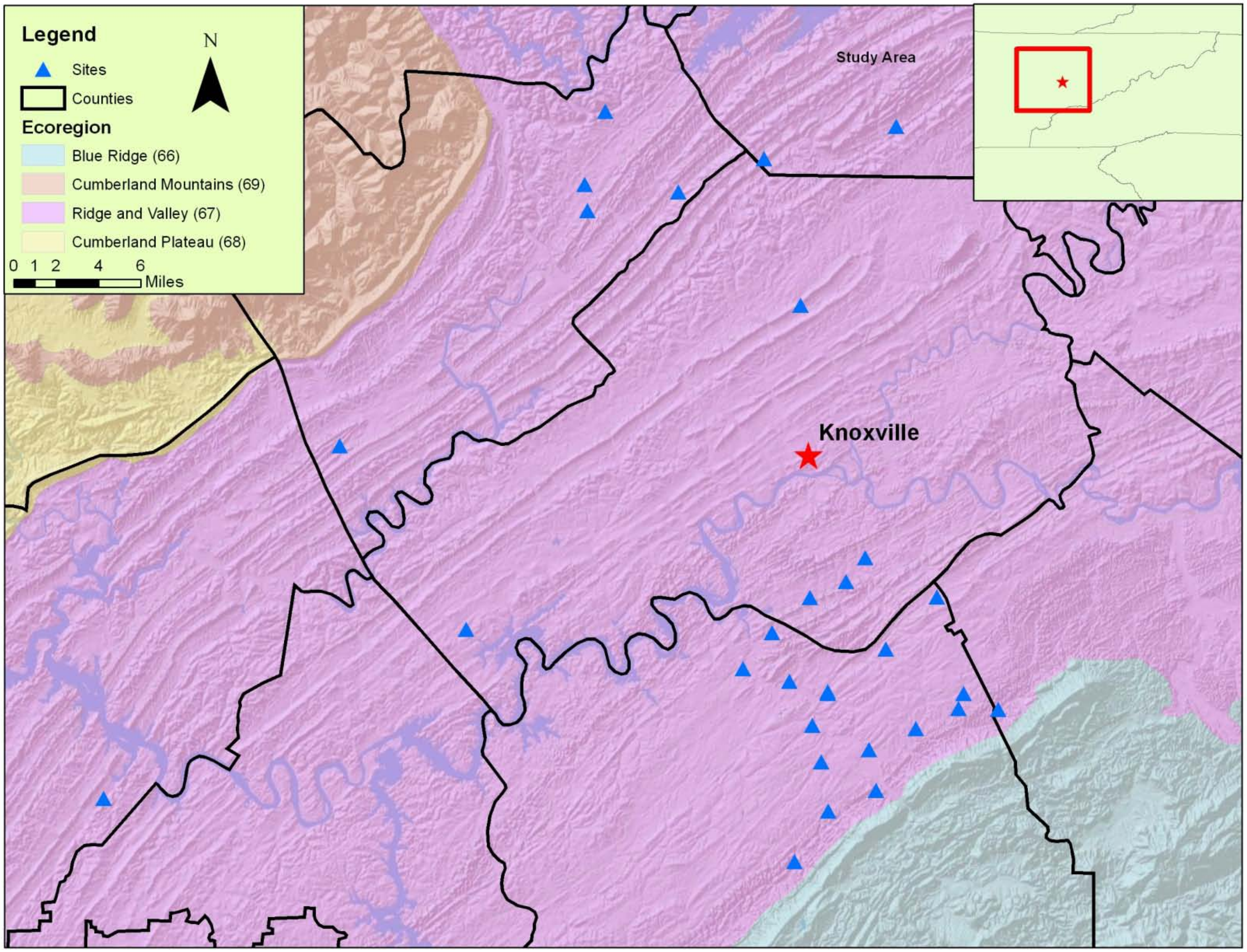

Figure 1. Site Locations within the Ridge and Valley Ecoregion.

Table 1. Site Coordinates and Geographic Information

TDEC Station ID	Stream Name	Latitude	Longitude	County	Ecoregion
BUFFA001.1AN	Buffalo Creek	36.16407	-84.07822	ANDERSON	67f
BULLR032.2UN	Bullrun Creek	36.19920	-83.81440	UNION	67f
BULLR1T0.6UN	Bullrun Creek	36.17907	-83.92644	UNION	67f
CARTE000.1SV	Carter Creek	35.79878	-83.73975	SEVIER	67i
COX000.2KN	Cox Creek	36.07840	-83.89830	KNOX	67i
CROOK007.2BT	Crooked Creek	35.73172	-83.88409	BLOUNT	67g
ECO67F06	Clear Creek	36.21361	-84.05972	ANDERSON	67f
ELLEJ000.1BT	Ellejoy Creek	35.77325	-83.84909	BLOUNT	67f
ELLEJ008.0BT	Ellejoy Creek	35.80000	-83.77300	BLOUNT	67g
FECO67I12	Mill Branch	35.98833	-84.28888	ANDERSON	67i
FLAG000.1BT	Flag Branch	35.76548	-83.88941	BLOUNT	67f
HINDS006.8AN	Hinds Creek	36.14605	-84.07650	ANDERSON	67f
HINDS014.1AN	Hinds Creek	36.15758	-83.99930	ANDERSON	67i
HOLLY000.5BT	Hollybrook Branch	35.82130	-83.91458	BLOUNT	67f
LELLE000.2BT	Little Ellejoy Creek	35.78700	-83.80924	BLOUNT	67g
LTURK001.4KN	Little Turkey Creek	35.86110	-84.18530	KNOX	67f
MCCAL000.9KN	McCall Creek	35.90468	-83.84851	KNOX	67g
NAILS000.7BT	Nails Creek	35.81360	-83.88261	BLOUNT	67g
NAILS004.5BT	Nails Creek	35.87660	-83.78890	BLOUNT	67g
NAILS008.3BT	Nails Creek	35.84190	-83.83310	BLOUNT	67f
PEPPE000.7BT	Peppermint Branch	35.79074	-83.89604	BLOUNT	67f
PITNE000.8BT	Pitner Branch	35.81027	-83.76829	BLOUNT	67g
PROCK003.1RO	Paint Rock Creek	35.74950	-84.49220	ROANE	67f
ROCKY000.8BT	Rocky Branch	35.74535	-83.84397	BLOUNT	67i
RODDY000.6BT	Roddy Branch	35.85472	-83.92823	BLOUNT	67f
RUSSE000.9BT	Russel Branch	35.83044	-83.95330	BLOUNT	67f
SFCRO001.0BT	SF Crooked Creek	35.69780	-83.91340	BLOUNT	67i
STOCK003.2KN	Stock Creek	35.87810	-83.89560	KNOX	67g
STOCK005.3KN	Stock Creek	35.88860	-83.86500	KNOX	67g
WILDW000.1BT	Wildwood Branch	35.81218	-83.88255	BLOUNT	67f

2.3 Tennessee Macroinvertebrate Index Data

Samples collected from SQSH surveys are used to calculate a score based on several characteristics of the sample, referred to as the Tennessee Macroinvertebrate Index. Attributes of the index include characteristics such as taxonomic richness of the sample, total number of genera of *Ephemeroptera,* *Plecoptera, and Trichoptera* (mayflies, stoneflies, and caddisflies, respectively), and the percentage of sample consisting of species tolerant to nutrients (TDEC 2006). The TMI is discussed in more detail in Section 1.2.3. The most recently updated Microsoft Access Database was obtained from TDEC. TMI data for each site sampled were extracted and compiled into a Microsoft Excel spreadsheet.

2.4 Field Logistics

In the field, approximate site locations were found using GPS coordinates and location descriptions found in the TDEC database. The field crew then walked upstream and downstream, approximately 50–100 meters, searching for an appropriate riffle at which to perform the survey. The highest quality riffle, based on substrate composition, length, and flow, respectively, was selected. We attempted to minimize disturbance of the substrate within the wetted channel to avoid compromising measurements.

Once we identified an appropriate riffle, photos of the channel and banks were taken, as well as notes on surrounding land use, riparian vegetation, and any apparent sediment inputs. Work then proceeded in the following order:

1. Construct grid for substrate characterization,
2. Perform pebble-count and embeddedness estimates at pre-determined locations on grid,
3. Collect fine sediment samples using “quoror” method or grab-samples,
4. Measure slope of the riffle.

2.5 Substrate Characterization

2.5.1 Modified EMAP Protocol

Substrate and embeddedness were characterized using a method based on the EPA Environmental Monitoring and Assessment Protocol (EMAP) (EPA 2001). EMAP combines several different methods outlined by Wolman (1954), Bain et al. (1985), Platts et al. (1983), and Plafkin et al. (1989) (EPA 2001). This method was chosen for its ability to detect known changes in sediment transport downstream of a dam (Sennatt et al. 2006).

In the EMAP protocol, 21 evenly spaced cross-sections are sampled along a transect having the length of 40 times the wetted width of the channel at low flow. In this study, the procedure was modified so that all 21 cross-sections were within riffles that are sampled during TDEC's Semi-Quantitative Single-Habitat surveys. At odd-numbered cross-sections (11 total) on each reach, the team visually estimated embeddedness, measured substrate particle size, and measured water depth at 0%, 25%, 50%, 75%, and 100% of the wetted-width. At even numbered cross-sections (total of 10), water depth and substrate particle size were measured. Upon completion, a total of 55 embeddedness, 105 particle-size, and 105 depth data points were measured systematically throughout the riffle.

In the field, transects were constructed by running one measuring tape longitudinally along the water's edge, and another perpendicular to the bank at the calculated locations along the transect. The field data sheet used during surveys can be found in Appendix 1.

2.5.2 Pebble Counts

Based on the method developed by Wolman (1954), pebble counts are conducted in the EMAP protocol by selecting the substrate particle located beneath a sharpened meter stick or surveyor's rod at 0%, 25%, 50%, 75%, and 100% of the wetted width. Each particle is then measured along the median (β) axis. Although EPA EMAP protocol calls for a visual estimation of the particle size, a gravelometer was used to ensure data consistency. Particles were coded and lumped into size classes (Table 2) based on the Wentworth scale. Upon completion of each survey, a total of 105 particles are measured.

Table 2. Particle Size Classes Used during Pebble-Counts

Size Class	**Size Range mm, β-axis**	**Code**
Bedrock	>4000	RR
Hardpan	Not Applicable	HP
Boulder	250-400	BL
Cobble	64-250	CB
Gravel (Coarse)	16-64	GC
Gravel (Fine)	2-16	GF
Sand	0.06-2	SA
Fines	<0.06	FN

2.5.3 EMBEDDEDNESS

Embeddedness was estimated within a 10-cm diameter circle centered at the substrate sampling point for each wetted-width interval. For this study, embeddedness was considered “the fraction of a particle’s (gravel or larger) surface that is surrounded (embedded in) sand or finer sediments on the stream bottom” (EPA 2001). Embeddedness was determined by estimating the degree to which gravel and larger particles are surrounded by sand and finer particles within a 10-cm wire ring and also by examining stains on gravel and larger particles (Figure 2) to determine the percentage of gravel and larger particles embedded in sand and finer particles.

Figure 2. Staining on a Cobble Particle from Clear Creek, Anderson County, Tennessee. The Reddish-Orange Area of the Rock Was Exposed to the Water Column and the Grey Area Was Embedded in the Substrate.

2.5.4 Metric Calculation

Pebble-count data were entered into a spreadsheet modified from the State of Ohio Department of Natural Resources reference reach survey spreadsheet (Mecklenburg 2004). The spreadsheet derives D_{84}, D_{50}, and D_{16}, as well as the proportion of the sample within each particle size class. D_{xx} refers to a specific percentile value of the distribution of particle ß-axis diameters. For instance, D_{50} represents the diameter at which 50% of the sample is larger and 50% smaller; D_{84} and D_{16} refer to the diameters for which 84 and 16%, respectively, of the sampled particles are smaller. These values are also important because they contain the portion of the sample within one standard deviation from the mean. Percentage of the sample finer than 2 mm (% < 2 mm) was then calculated from the pebble count data. Embeddedness estimates over the entire riffle were averaged to obtain one value for each site.

2.6 Fine Sediment in Gravel-Dominated Riffles

2.6.1 Fine Sediment Collection

In riffles dominated by coarse and fine gravels, the "quoror" method (NIWAR 2008) was used to collect fine sediments. In the "quoror" method, a bottomless cylinder is driven into the channel bed and substrate within the cylinder is stirred to create slurry, of which samples are taken.

In the field, background water samples were first taken at the head (upstream end) of the sample riffle. At the upstream section, midway point, and downstream section of the riffle, a bottomless cylinder was inserted into the channel bed. For consistency between sites, efforts were made to take the "quoror" sample at the center of the thalweg. If the flow was uniform, the sample was taken from the center of the riffle. Water depth was measured at five random locations within the cylinder. Using a rod, I stirred the substrate for one minute, after which two 120-mL samples of the slurry were taken. In order to express the results volumetrically, the depth of penetration was measured and recorded at five locations within the cylinder after the samples had been taken.

2.6.2 Fine Sediment Sample Processing

Samples collected using the "quoror" method were processed using EPA Environmental Sciences Section Method 340.2: Total Suspended Solids (EPA 1993). All samples were processed using ProWeigh pre-washed/weighed Total and Volatile Suspend Solids Analysis filters, a 1000 mL suction flask, and 47 mm glass microanalysis filter holder. All results were recorded and metrics calculated using Microsoft Excel. The steps in the process are as follows:

1. Weigh filter.
2. Record filter dish ID and weight and place on filter holder attached to vacuum flask.
3. Volumetrically transfer sample with a pipette onto TSS filter and record volume.
4. Dry filter containing sample for at least one hour in 105^{o} C oven.

5. Cool in desiccator and record weight of filter with sample.

6. Calculate Total Suspended Solids (TSS):

$$TSS = \frac{(A - B) * 1000}{C}$$

A= Filter with Residue

B= Filter

C= Sample Volume

7. Correct TSS for background TSS value:

$TSS_{substrate} = TSS_{sample} - TSS_{background}$

8. Ignite filter containing dry sample for 30 minutes in 550^{o} C muffle furnace

9. Cool in desiccator and record weight.

10. Calculate Volatile Suspended Solids (VSS):

$$VSS = \frac{(A - B) * 1000}{C}$$

A= Pre-ignition filter weight
B= Post-ignition filter weight
C= Sample volume

10. Correct VSS for background:

$VSS_{substrate} = VSS_{sample} - VSS_{background}$

11. Calculate Suspendable Inorganic Sediments (SIS) (NIWA 2008):

Areal SIS= ($TSS_{corrected}$ – $VSS_{corrected}$) x Average water depth

Volumetric SIS= Areal SIS/(Average stir depth – Average water depth)

12. Calculate Suspendable Organic Sediments (SOS) (NIWA 2008):

Areal SOS= $VSS_{corrected}$ x Average water depth

Volumetric SOS= Areal SOS/(Average stir depth – Average water depth).

2.7 Fine Sediment in Cobble-Dominated Riffles

2.7.1 Fine Sediment Collection

In cobble-dominant riffles, three grab samples were taken in random locations in the sample riffle to quantify the proportion of particles greater than 2 mm, 1–2 mm, and less than 1 mm. Samples were taken at the upstream, middle, and downstream section of the riffle. Samples were taken by scooping gravel, sand, and fine sediment material deposited behind cobble or larger-sized particles.

2.7.2 Fine Sediment Sample Processing

Sediment samples from cobble-dominated riffles were processed using sieve analysis. All measurements were recorded and percentages calculated using Microsoft Excel. Samples were processed as follows:

1. Record beaker weight.
2. Air dry sample.
3. Transfer sample into beaker and dry in oven for 24 hours at 108^0 C.
4. Stack sieves with largest screen opening on top and pour sample into sieve.
5. Shake sieve for five minutes.

6. For each sieve, transfer material into a pre-weighed beaker and record weight.
7. Calculate the proportion of each particle size class:

   % of sample in size class = Retained material weight/Total sample weight.

2.8 Variation in Bed Sediment Characteristics over Time

To assess the variation in riffle sediment over time, I monitored three sites a total of six times between February 2010 and November 2010. Monitoring sites included Nails Creek (NAILS000.1BT), Pitner Branch (PITNE000.8BT), and Clear Creek (ECO67F17). Nails Creek and Pitner Branch are 3rd-order tributaries of the Little River in Blount County. Clear Creek is a 2nd -order tributary to the Clinch River below Norris Dam in Anderson County and a TDEC reference stream. At each site, bed sediment in riffles was characterized using pebble counts and embeddedness estimates as described in sections 2.6.2 and 2.6.3, respectively.

2.9 Statistical Analysis

2.9.1 Relationships Between Bed Sediment and Benthic Impairment

All TMI and sediment data were compiled into an Excel spreadsheet and imported into SPSS 18.0 for statistical analysis. During analysis, I treated TMI scores as a dependent variable and sediment metrics, derived from field collections and laboratory procedures, as independent variables.

One-sample Kolmogorov-Smirnov tests were used to test whether data showed a normal distribution. Bivariate correlation analysis, using both Pearson and Spearman Rank Correlation Coefficients for normal and non-normal data, respectively, was used to determine whether bed sediment characteristics were correlated with TMI scores.

To assess the potential use of substrate metrics to monitor water quality goals, I grouped TMI data into non-impaired, slightly impaired, moderately impaired, and severely impaired categories using criteria outlined by TDEC (TDEC 2006). These categories indicate the degree of impairment for each stream reach based on a TMI score. Initially, box and whisker plots were used to compare metrics between groups of impairment. Box plots display the five-number summary of a variable—median, upper quartile, lower quartile, minimum, and maximum observations. I then used One-Way Analysis of Variance (ANOVA) and Kruskal-Wallace tests (K-W) to examine statistically significant differences between groups of impairment with respect to the substrate metrics.

2.9.2 Logistic Regression

To test the predictive capability of substrate metrics on benthic habitat status, I used a logistic regression model. Logistic regression is a technique that can be used to test the response of a categorical dependent variable, such as benthic impairment, from a continuous independent variable(s), such as a substrate metric.

As opposed to Ordinary Least Squares (OLS) regression, in which the magnitude of a response variable is modeled as a function of one or more continuous explanatory variables, the logistic regression equation predicts the probability of being in one of the categorical groups as a function of the continuous independent variables (Helsel and Hirsch 1992). The result is an equation explaining the relationship of the variables in the model:

$$\log\left(\frac{p}{1-P}\right) = b_0 + bX$$

In the equation, b_0 is the intercept, X is a vector of k explanatory variables, and bX includes the slope coefficients of all explanatory variables, so that $bX = b_1X_1, b_2X_2,\ldots b_kX_k$ (Helsel and Hirsch 1992). The slope coefficients are then fit to the response variable using the Maximum Likelihood Estimation (MLE) method. In short, MLE is concerned with choosing parameter estimates that have the highest probability of the correct response category based on actual observations (Aldrich and Nelson 1984).

To test model fit, I used Cox & Snell (1989) and Nagelkerke (1991) pseudo-R^2 values, Hosmer and Lemeshow (2000) tests, Omnibus test of model coefficients, and classification rates. In OLS, the R^2 value indicates the percent of variance of the dependent variable explained by the independent variable. Although there is no direct complement of the R^2 in logistic regression, several pseudo-R^2 values were used in this study to compare the predictive capability between models. The Homer and Lemeshow test determines whether there is a significant difference between the observed values and the values predicted by the model. Rejecting the null hypothesis (when $p<0.05$) indicates that there is a significant difference between the observed and predicted values. Therefore, the model adequately fits the data if $p >0.05$. The Omnibus test of model coefficients tests whether the model with the explanatory variable is significantly different from the model with the constant only. Classification rate reports the percent at which the model correctly predicts the dependent variable.

For this study, benthic impairment, as determined by TMI scores, was lumped into a binary dependent response variable. TMI scores greater than or equal to 32 were considered "non-impaired," and scores less than 32 were considered "impaired." This grouping is based on TDEC's biological criteria for macroinvertebrates (TDEC 2006). I used a univariate approach to model the response of the impairment variable as a function of an individual substrate metric.

CHAPTER THREE

3 RESULTS

To test hypotheses introduced in Chapter One, three sets of data were used—TMI data from TDEC, data collected in the field, and data derived from laboratory procedures. This chapter is divided into seven sections. The first two sections briefly describe TMI data extracted from the TDEC database and bed sediment characteristics derived from data collected in the field. Sections 3, 4, and 5 analyze relationships between bed sediment characteristics, TMI data, and benthic impairment using correlation analysis, ANOVA, and logistic regression models. Sections 6 and 7 describe and analyze data associated with interstitial sediment collected using the "quoror" method and cobble grabs. The last section examines patterns associated with variation in bed sediment characteristics over time by describing data collected at three monitoring sites over the course of a year. Raw data collected in this study are archived at the University of Tennessee Department of Geography.

3.1 TENNESSEE MACROINVERTEBRATE INDEX

A total of 30 TDEC sites are included in the dataset. TMI scores ranged from 18 to 40, with a mean of 30 and standard deviation of 5.585. Of these, 12 sites have been classified as non-impaired, 15 as slightly impaired, 3 as moderately impaired, and no sites as severely impaired.

3.2 Bed Sediment Characteristics

I characterized riffle substrate on the channel bed at a total of 30 sites between June 2009 and November 2010. A summary table of bed-sediment characteristics at each site is reported in Table 3. In the table, each row represents one site and columns represent bed-sediment characteristics. Particle size distribution curves for each study site are found in Appendix 2.

Table 3. Tennessee Macroinvertebrate Index and Bed Sediment Characteristics

Site ID	TMI Score	Impairment Status	Embeddedness (%)	D84 (mm)	D50 (mm)	D16 (mm)	% Finer 2mm
BUFFA001.1AN	18	Moderately-Impaired	31	42.00	4.90	0.06	35
BULLR01T.0UN	38	Non-Impaired	50	74.00	3.90	0.06	42
BULLR032.2UN	36	Non-Impaired	33	80.00	22.00	3.40	8
CARTE000.1SE	34	Non-Impaired	36	120.00	20.00	0.17	34
COX000.2KN	24	Slightly-Impaired	38	90.00	4.30	0.06	36
CROOK007.2BT	36	Non-Impaired	38	240.00	80.00	0.29	24
ECO67F06 (Clear Creek)	34	Non-Impaired	27	42.00	10.00	1.60	14
ECO67I12 (Mill Branch)	38	Non-Impaired	44	47.00	11.00	0.11	29
ELLEJ000.1BT	20	Moderately-Impaired	60	120.00	1.40	0.15	49
ELLEJ008.0BT	26	Slightly-Impaired	87	3.20	0.35	0.06	75
FLAG000.1BT	24	Slightly-Impaired	89	8.60	0.10	0.06	66

Site ID	TMI Score	Impairment Status	Embeddedness (%)	D84 (mm)	D50 (mm)	D16 (mm)	% Finer 2mm
HINDS006.8AN	30	Slightly-Impaired	45	59.00	7.40	0.06	36
HINDS014.1AN	32	Non-Impaired	60	86.00	6.00	0.06	40
HOLLY000.5BT	20	Moderately-Impaired	68	48.00	7.00	0.06	30
LELLE000.2BT	26	Slightly-Impaired	75	5.30	0.21	0.06	61
LTURK001.4KN	28	Slightly-Impaired	61	76.00	4.40	0.08	40
MCALL000.2KN	22	Slightly-Impaired	62	19.00	0.35	0.06	51
NAILS000.7BT	30	Slightly-Impaired	62	35.00	3.50	0.06	43
NAILS004.5BT	30	Slightly-Impaired	66	48.00	0.84	0.06	53
NAILS008.3BT	32	Non-Impaired	87	12.00	0.37	0.06	63
PEPPE000.7BT	28	Slightly-Impaired	84	4.70	0.06	0.06	70
PITNE000.8BT	30	Slightly-Impaired	50	58.00	17.00	0.06	35
PROCK003.1RO	40	Non-Impaired	38	80.00	17.00	0.34	26
ROCKY000.1BT	32	Non-Impaired	68	16.00	2.00	0.06	46
RODDY000.6BT	30	Slightly-Impaired	84	6.30	0.17	0.06	61
RUSSE000.9BT	28	Slightly-Impaired	67	110.00	1.60	0.09	51
SFKCR000.1BT	28	Slightly-Impaired	96	1.20	0.15	0.06	83
STOCK003.2KN	34	Non-Impaired	30	200.00	67.00	1.60	16
STOCK005.3KN	34	Non-Impaired	50	15.00	3.50	0.15	34
WILDW000.1BT	28	Slightly-Impaired	46	350.00	5.10	0.06	25

3.3 Relationships between Bed Sediment Characteristics and TMI Scores

To test hypotheses associated with bed sediment characteristics and TMI scores, I used bivariate correlation analysis to examine relationships between TMI data and sediment metrics. One-sample Kolmogorov-Smirnov tests indicated that embeddedness, D_{84}, and %<2mm were distributed normally. The metrics D_{50} and D_{16} were not distributed normally.

Pearson correlation coefficients and Spearman rank correlation coefficients were computed for normally and non-normally distributed data, respectively (Table 4). Correlation coefficients associated with fine sediment metrics partially supported the alternative hypothesis that, as fine sediment on the channel bed increases, TMI scores decrease. I expected to see significant negative relationships between embeddedness and %<2mm. Visually estimated embeddedness showed a negative, but not significant relationship with TMI scores, while %<2mm, quantitatively derived from pebble counts, showed a significant negative correlation with TMI scores. Significant positive correlations between D_{50} and TMI supported the second alternative hypothesis.

No particularly strong correlations exist between TMI scores and bed sediment metrics (**Table 4**). The strongest correlations were with D_{50}, D_{16}, and %<2mm. Although, correlations were subtle, the presence of several statistically significant correlations between TMI scores and bed sediment metrics indicate that underlying relationships are present in the data. In addition to relationships between TMI scores and sediment metrics, relationships between visually estimated embeddedness and quantitative metrics derived from pebble counts were also examined. Embeddedness showed strong correlations with all quantitative pebble-count metrics (Table 5). In particular, embeddedness had the strongest correlation with %<2mm (r_s=0.879, p<0.001) and with D_{50} (r_s=-0.848, p<0.001). This supports the third alternative hypothesis that embeddedness is negatively correlated with D_{84}, D_{50}, and D_{16} and positively correlated with % finer than 2mm.

Table 4. Normality and Correlation of Bed Sediment Characteristics to TMI scores

Variable (against TMI)	K-S p-value[1]	Correlation Coefficient (p-value)	
		Pearson	**Spearman**
Embeddedness	0.805	-0.35 (0.059)	-0.439 (0.015)*
%<2mm	0.857	-0.389 (0.033)*	-0.489 (0.006)*
D84	0.211	0.163 (0.388)	0.250 (0.182)
D50	0.011	0.410 (0.024)*	0.553 (0.002)*
D16	<.001	0.345 (0.062)*	0.546 (0.002)*

[1]One-sample Kolmogorov-Smirnov Test. Value <0.05 indicates data are not normally distributed.
*Correlation is significant at the 0.05 level

Table 5. Nonparametric Correlation Coefficient Matrix of Bed Sediment Characteristics

	Embeddedness	**D84**	**D50**	**D16**	**% < 2mm**
Embeddedness	1.000	-	-	-	-
D84	-0.700**	1.000	-	-	-
D50	-0.848**	0.744**	1.000	-	-
D16	-0.631**	0.516**	0.608**	1.000	-
% < 2mm	0.879**	-0.697**	-0.919**	-0.651**	1.000

**Correlation is significant at the 0.01 level

3.4 Sediment Characteristics and Benthic Impairment

One-way Analysis of Variance (ANOVA) and Kruskal-Wallace (K-W) tests were used to test if the mean or median, respectively, differed between groups of impairment. A p value of less than 0.05 indicates that the mean or median is significantly different between groups and allows rejection of the null hypothesis that mean or median bed sediment characteristics are statistically similar between groups. However, this type of analysis does not indicate which of the groups differ. To further narrow differences between groups, I used pairwise t-tests or Mann-Whitney U tests, depending on the distribution of the data.

ANOVA analysis of sediment metrics between groups supported the alternative hypothesis and revealed statistically significant differences between groups of impairment for embeddedness (p =0 .019) and % finer than 2mm (p = 0.005). To further investigate differences between groups, I used two-independent sample T-tests to compare means of sediment metrics between non-impaired and slightly impaired, moderately impaired and slightly impaired, and non-impaired and moderately impaired groups. Analysis revealed statistically significant differences in means between non-impaired and slightly impaired groups, but no statistically significant difference in means between non-impaired and moderately impaired or the moderately impaired and slightly impaired groups. The lack of significant differences may be a result of the small number of moderately impaired sites (three) in the dataset, resulting in a low statistical power in the analysis.

Reducing the number of groups in the analysis, by combining slightly impaired and moderately impaired categories into one group, and comparing impaired versus non-impaired groups, yielded statistically significant differences between the groups for mean embeddedness ($p < 0.001$) and mean % finer than 2 mm ($p < 0.001$). The impaired group had a mean embeddedness of 68% and mean %<2mm of 50%, while the non-impaired group had a mean embeddedness of 38% and %<2mm of 25%. Differences in fine sediment metrics, with respect to impairment status, are illustrated using boxplots in Figures 3 and 4.

Kruskal-Wallace tests were used to test for differences in median between impairment groups for D_{50} and D_{16}. K-W is a non-parametric approach to testing for differences in the median between groups. Similar to the relationships determined for embeddedness and %<2mm, both D_{50} and D_{16} were significantly different between non-impaired and slightly impaired groups, but not significantly different between slightly impaired and moderately impaired or between non-impaired and moderately impaired groups. However, combining the two middle classes, slightly impaired and moderately impaired, into one "impaired" category yielded statistically significant differences between the groups for D_{50} ($p=0.001$) and D_{16} ($p<0.001$). Differences in D_{84}, D_{50}, and D_{16}, with respect to impairment status, are illustrated using box plots in Figures 4, 6, and 7.

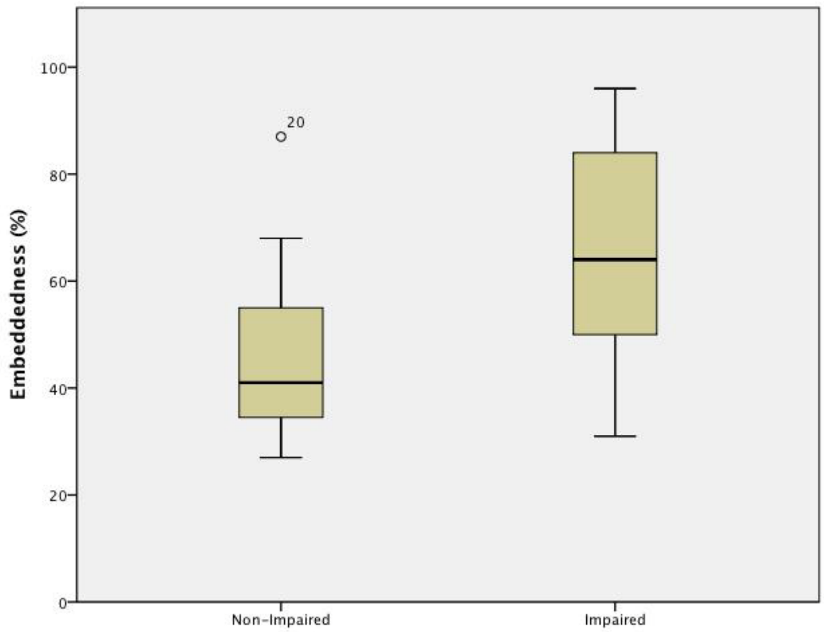

Figure 3. Box and Whisker Plots of Embeddedness Grouped into Non-Impaired (n = 12) and Impaired (n = 18).

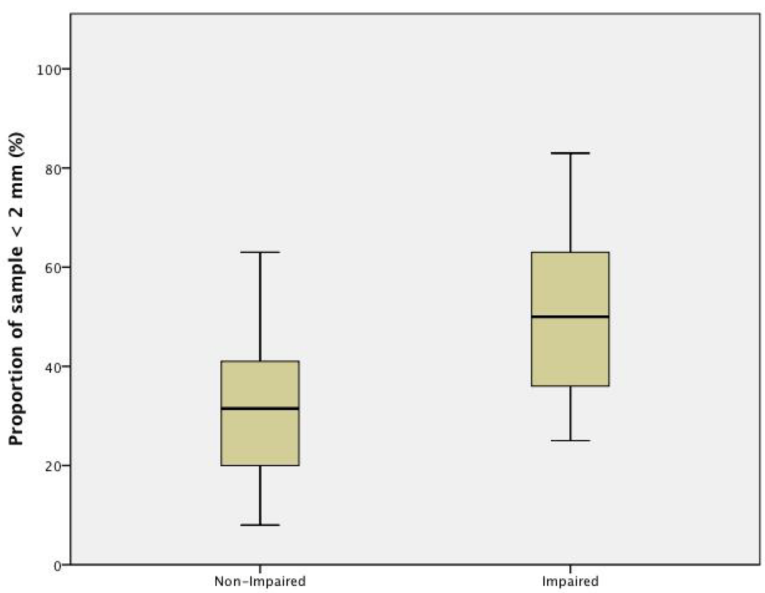

Figure 4. Box and Whisker Plots of % Less than 2 mm Grouped into Non-Impaired (n = 12) and Impaired (n = 18).

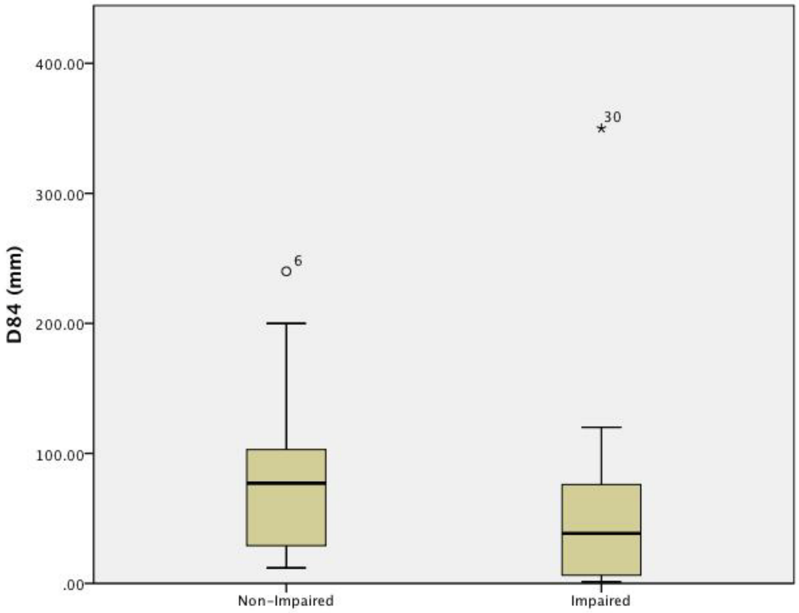

Figure 5. **Box and Whisker Plots of D_{84} Grouped into Non-Impaired (n = 12) and Impaired (n = 18).**

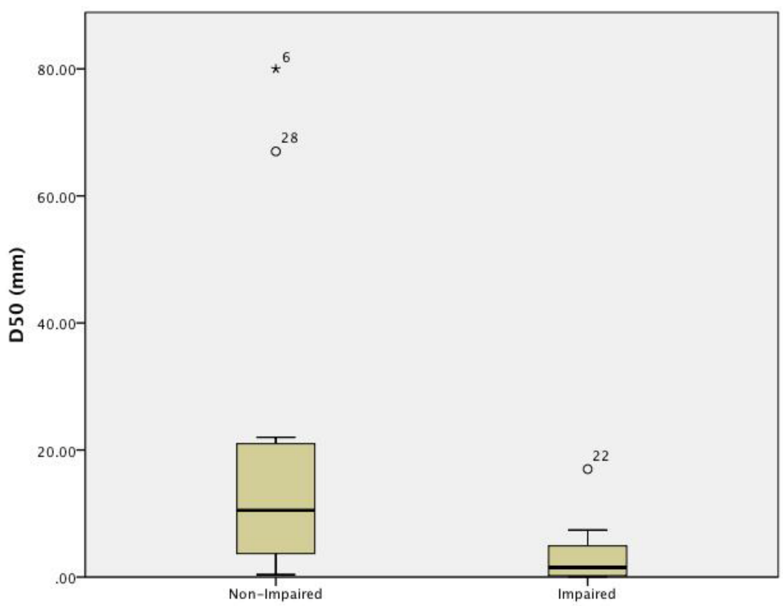

Figure 6. **Box and Whisker Plots of D_{50} Grouped into Non-Impaired (n = 12) and Impaired (n = 18).**

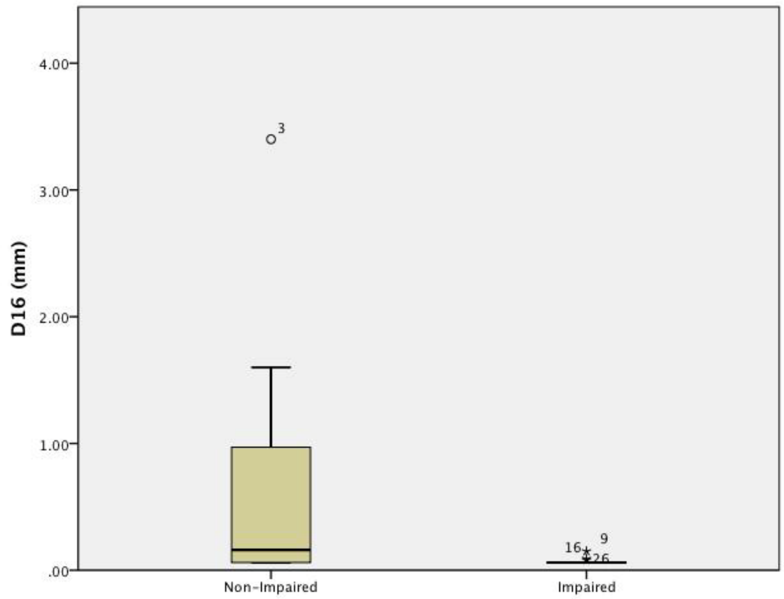

Figure 7. Box and Whisker Plots of D_{16} Grouped into Non-Impaired (n = 12) and Impaired (n = 18).

3.5 LOGISTIC REGRESSION

Logistic regression models were developed to test the predictive capability of substrate metrics with respect to benthic impairment. In this study, logistic regression tests the response of a categorical dependent variable (benthic impairment) to a continuous independent variable (substrate metric).

In univariate models, four of the five explanatory variables—embeddedness, %<2mm, D_{50}, and D_{16} —showed significant relationships with benthic impairment. Table 6 summarizes parameters, equation coefficients, and goodness-of-fit statistics for outputs of the logistic regression models. Hosmer and Lemeshow tests on all models with significant explanatory variables had p values greater than 0.05, indicating the predicted values from the model were not significantly different from the observed values. Similarly, omnibus tests of model coefficients were significant for all explanatory variables, indicating that equations with explanatory variables were significantly different from those with only the constant values. Cox & Snell and Nagelkerke pseudo-R^2 values were relatively similar for all significant variables, suggesting that all substrate parameters performed similarly when predicting impairment. Overall, output from the univariate logistic regression models suggests that substrate metrics are significant predictors of benthic impairment, leading me to reject the null hypothesis.

A logistic regression model with all substrate metrics was developed using the forward stepwise method. The final model output only retained % less than 2 mm as an explanatory variable. Classification rates for non-impaired and impaired sites were 67% and 78%, respectively. The overall classification rate was 73%.

Table 6. Logistic Regression Output and Associated Goodness-of-Fit Statistics for Univariate Models of Substrate Metrics

	Equation Values[1]						Goodness-of-Fit Statistics[2]					Classification Rate (%)		
Explanatory Variable	**B**	**S.E.**	**Wald**	**df**	**Sig.**	**Exp(B)**	**H-L[2] (p-value)**	**Omnibus Coefficient (p-value)**	**Log likelihood**	**Cox & Snell R Square**	**Nagelkerke R Square**	**Non-Impaired**	**Impaired**	**Overall**
Embeddedness	0.06	0.03	5.23	1	0.02	1.06	5.263 (0.729)	6.89 (.009)	33.49	0.21	0.28	58	78	70
Constant	-2.79	1.41	3.95	1	0.05	0.06								
% < 2mm	0.080	0.033	5.854	1	.016	1.084	8.99 (0.253)	9.323 (.002)	31.057	0.267	0.361	67	78	73
Constant	-2.822	1.337	4.459	1	0.035	0.059								
D84	-0.004	0.005	0.779	1	.377	0.996	6.02 (0.645)	0.824 (0.364)	39.557	0.027	0.037	17	94	63
Constant	0.715	.515	1.930	1	0.165	2.044								
D50	-0.181	0.083	4.708	1	0.030	0.834	6.057 (0.641)	10.553 (0.001)	29.827	0.297	0.401	58	94	80
Constant	1.628	0.635	6.563	1	0.010	5.094								
D16	-25.344	13.439	3.556	1	0.059	0.000	1.204 (0.752)	14.124 (<0.001)	26.257	0.375	0.508	58	94	80
Constant	2.935	1.171	6.286	1	0.012	18.817								

[1]Equation values: B = Slope coefficient; S.E. = Standard Error of B; Wald = Wald Statistic; Sig. = Significance value for the Wald Statistic; Exp(B) = odds ratio

[2]H-L = Hosmer and Lemeshow test

3.6 Fine Sediment in Gravel and Cobble Dominated Riffles

3.6.1 Gravel-Dominated Riffles

To investigate the relationship between TMI and interstitial sediments in gravel-bed reaches, samples collected using the “quoror” were processed in the lab, using standard protocols for processing total suspended solids, and then compared to TMI data. I collected quoror samples at a total of 23 sites in the study area. Among sites, Areal Suspendable Inorganic Sediment (SIS) had a mean of 1420 g/m^2, with standard deviation of 805 g/m^2; Volumetric SIS had a mean of 8351 g/m^3, with standard deviation of 4979 g/m^3; Areal Suspendable Organic Sediment (SOS) had a mean of 100 g/m^2,with standard deviation of 52 g/m^2; and Volumetric SOS had a mean of 5769 g/m^3, with standard deviation of 4315 g/m^3 (Table 7).

Correlation analysis yielded no statistically significant relationships between fine sediment collected using the “quoror” method and TMI scores (Table 8); thus I was unable to reject the null hypothesis. Additionally, no relationships between bed sediment metrics or fine sediment collections were statistically significant.

Table 7. Tennessee Macroinvertebrate Index and Interstitial Sediment Characteristics

Site ID	TMI Score	Impairment	Areal SIS[1] (g/m2)	Volumetric SIS[1] (g/m3)	Areal SOS[2] (g/m2)	Volumetric SOS[2] (g/m3)
BUFFA001.1AN	18	Moderately-Impaired	1664	8097	136	4241
BULLR032.2UN	36	Non-Impaired	1946	11880	132	7320
COX000.2KN	24	Slightly-Impaired	2369	16327	144	7260
ECO67F06 (Clear Cr.)	34	Non-Impaired	145	1762	16	3434
ECO67I12 (Mill Branch)	38	Non-Impaired	2166	6738	185	3334
ELLEJ008.0BT	26	Slightly-Impaired	2036	7713	168	3726
FLAG000.1BT	24	Slightly-Impaired	794	9856	55	12416
GALLA002.6BT	36	Non-Impaired	2745	15907	148	6656
HINDS006.8AN	30	Slightly-Impaired	930	3587	69	1578
HOLLY000.5BT	20	Moderately-Impaired	871	9387	76	13463
LELLE000.2BT	26	Slightly-Impaired	1723	10181	101	4681
MCALL000.2KN	22	Slightly-Impaired	2728	18510	172	11540
NAILS000.7BT	30	Slightly-Impaired	920	3731	78	1604
NAILS004.5BT	30	Slightly-Impaired	193	1290	14	883
NAILS008.3BT	32	Non-Impaired	623	3506	44	2332
PEPPE000.7BT	28	Slightly-Impaired	1256	8073	100	5718
PITNE000.8BT	30	Slightly-Impaired	914	5522	81	4379
PROCK003.1RO	40	Non-Impaired	2157	6860	121	1627
ROCKY000.1BT	32	Non-Impaired	1947	15673	145	15925
RODDY000.6BT	30	Slightly-Impaired	2326	12590	174	8155
RUSSE000.9BT	28	Slightly-Impaired	1041	4316	71	1754
SFKCR000.1BT	28	Slightly-Impaired	319	1998	26	1237
STOCK005.3KN	34	Non-Impaired	849	8585	64	9434

[1]SIS- Suspendable Inorganic Sediment
[2]SOS- Suspendable Organic Sediment

Table 8. Correlation Coefficients of Interstitial Sediment Values to TMI Scores

Variables (Against TMI Score)	**Pearson Correlation Coefficient**	**Significance**
Areal SIS (gm2)	0.063	0.774
Volumetric SIS (gm3)	-0.18	0.411
Areal SOS (gm2)	0.007	0.973
Volumetric SOS (gm3)	-0.284	0.188

3.6.2 Cobble-Dominated Riffles

Grab samples were collected at a total of seven sites during the study (Table 9). Among sites, the mean proportion larger than 2 mm was 66% ± 15%, mean proportion 1mm–2mm was 20% ± 8%, and mean proportion < 1 mm was 16% ± 13%. Grab samples showed no particular pattern with respect to TMI scores.

Table 9. Summary Table of Data Derived from Cobble-Grab Samples

Site ID	TMI	> 2mm (%)	1mm-2mm (%)	< 1mm (%)
CARTE000.1SE	34	71	15	13
CROOK007.2BT	36	56	27	17
ELLEJ000.1BT	20	38	35	42
HINDS014.1AN	32	86	10	4
LTURK001.4KN	28	67	19	14
STOCK003.2KN	34	68	14	18
WILDW000.1BT	28	78	22	1

3.7 Variation in Bed Sediment Characteristics over Time

To examine variation of bed sediments over time, I monitored three sites over the course of a year. Bed sediment was characterized at Nails Creek (NAILS00.1BT), Pitner Branch (PITNE000.8BT), and Clear Creek (ECO67F17) every other month, totaling six surveys per site, during 2010. Summary tables of bed sediment characteristics for each site are found in Table 10, Table 11, and Table 12.

Clear Creek, a TDEC reference stream, had a D_{50} ranging between 9.8 and 19.0 mm (fine to coarse gravel). Although surveyed, data for this site are currently missing for October. This site showed little variation in embeddedness, with the exception of July, when it dropped considerably, from 30% to 16%. Percent finer than 2 mm showed little variation, ranging between 10% and 13%.

At Nails Creek, D_{50} was fine gravel throughout the year, ranging from 3.2 to 6.2 mm. This site showed considerable variation in embeddedness, ranging between 40% and 60%, with the lowest value in May and the highest value in November. Percent finer than 2 mm showed little variation, ranging between 32% and 42%.

D_{50} at Pitner Branch ranged between 3.6 and 17 mm, with the highest value in November and the lowest in February. This site showed little variation in embeddedness, ranging between 44% and 53%. Percent finer than 2 mm ranged between 31% and 47%.

Overall, D_{16} and D_{84} showed very little variation at all sites throughout the year. D_{50} did show some variation over time; however, variance was within one order of magnitude and D_{50} for all sites remained in the same respective size class categories throughout the year. Both embeddedness and percent finer than 2 mm showed some variation between months at some sites, but no consistent, seasonal pattern emerged. More data are needed to make conclusive observations as to the variation in substrate characteristics over time.

Table 10. Summary Table of Bed Sediment Characteristics for Data Collected between February 2010 and November 2010 in Clear Creek, Anderson County, Tennessee

Month	Date	Embeddedness	%<2mm	D84	D50	D16
February	2/13/10	34	10	180.00	19.00	2.20
April	4/3/10	32	12	41.00	13.00	2.10
May	5/18/10	30	12	64.00	9.80	2.10
July	7/22/10	16	13	57.00	16.00	1.80
October	NA	NA	NA	NA	NA	NA
November	11/11/10	30	13	41.00	11.00	1.90

Table 11. Summary Table of Bed Sediment Characteristics for Data Collected between February 2010 and November 2010 in Nails Creek, Blount County, Tennessee

Month	Date	Embeddedness	%<2mm	D84	D50	D16
February	2/16/10	52	42	39	3.6	0.062
April	4/1/10	53	34	46	11	0.062
May	5/2/10	38	37	41	5.5	0.062
July	7/21/10	50	40	52	4.8	0.062
October	10/12/10	53	38	41	4.9	0.062
November	11/9/10	60	32	39	6.2	0.062

Table 12. Summary of Bed Sediment Characteristics for Data Collected between February 2010 and November 2010 in Pitner Branch, Blount County, Tennessee

Month	Date	Embeddedness	%<2mm	D84	D50	D16
February	2/16/10	52	40	35	3.6	0.062
April	4/10/10	50	32	56	14	0.062
May	5/20/10	52	47	41	2.4	0.062
July	7/21/10	53	35	54	5.9	0.062
October	10/12/10	44	31	80	21	0.15
November	11/9/10	49	34	54	17	0.062

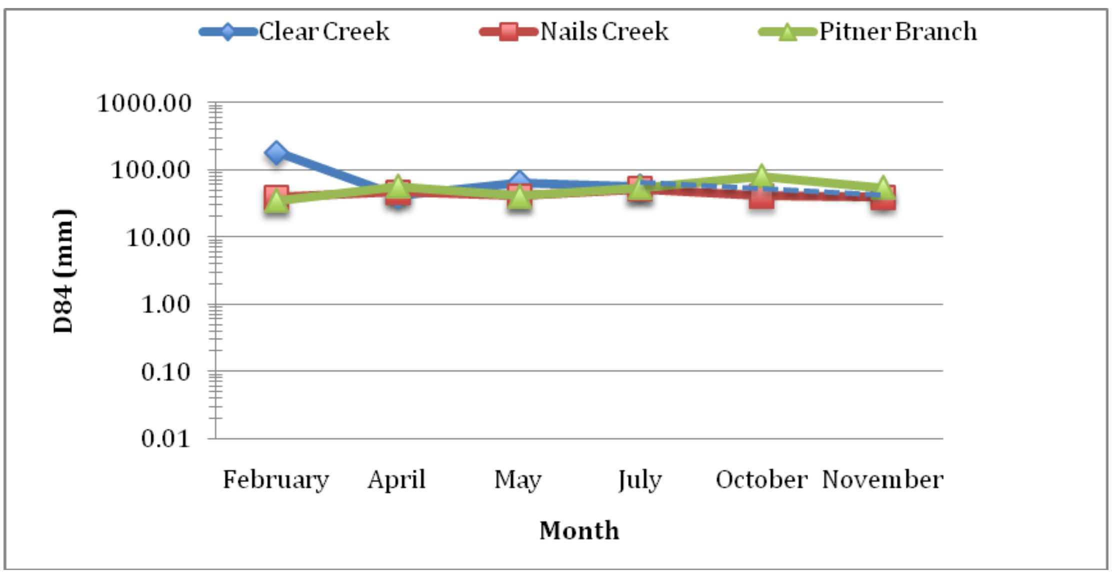

Figure 8. D_{84} by Month for Data Collected between February 2010 and November 2010. Dashed Line Represents Interpolated Data for Clear Creek for Missing October Data.

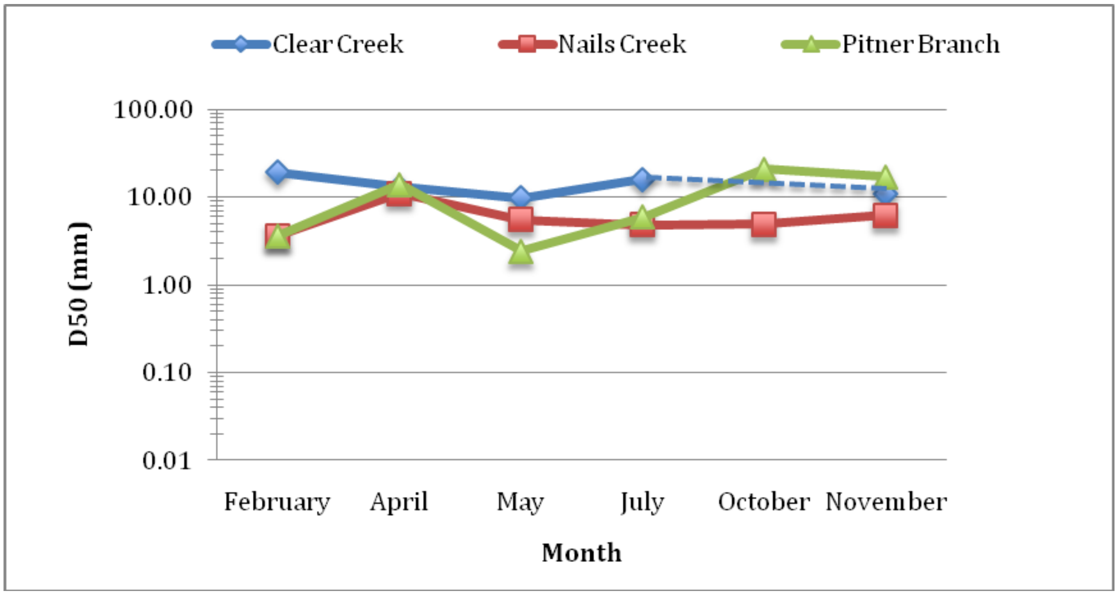

Figure 9. D_{50} by Month for Data Collected between February 2010 and November 2010. Dashed Line Represents Interpolated Data for Clear Creek for Missing October Data.

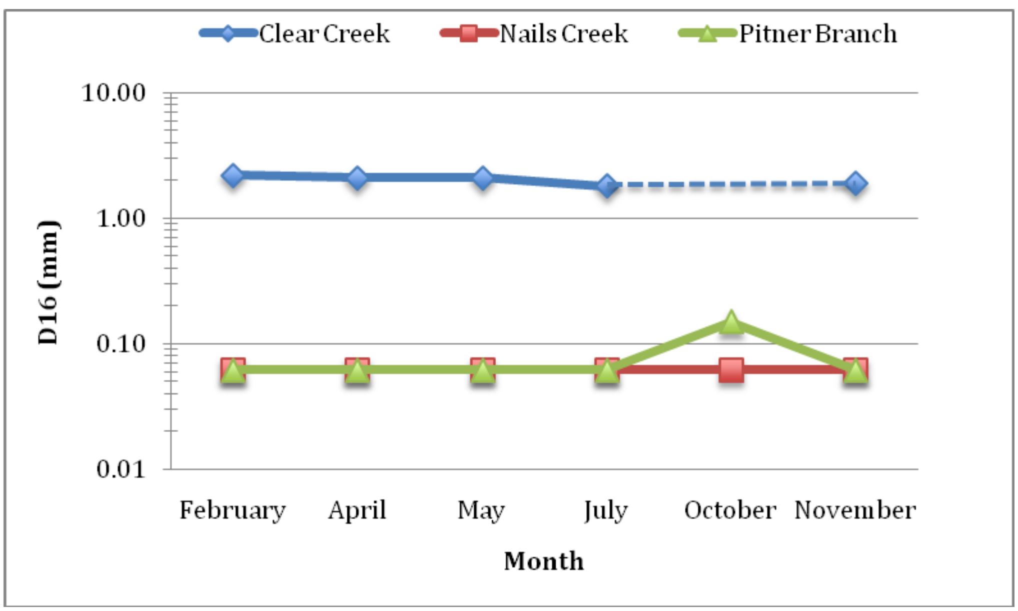

Figure 10. D_{16} by Month for Data Collected between February 2010 and November 2010. Dashed Line Represents Interpolated Data for Clear Creek for Missing October Data.

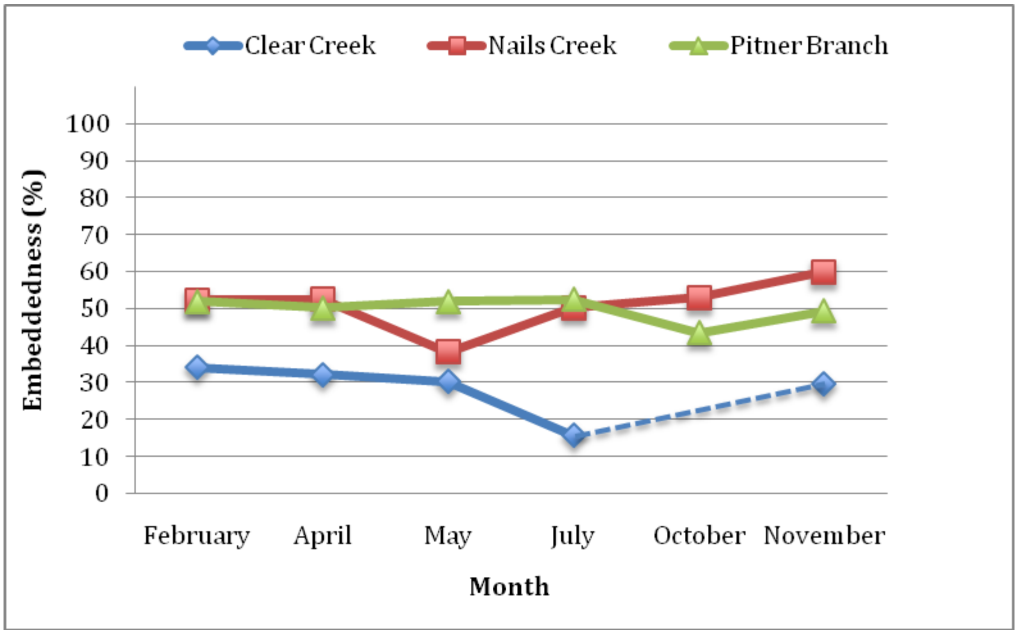

Figure 11. Embeddedness Values by Month for Data Collected between February 2010 and November 2010. Dashed Line Represents Interpolated Data for Clear Creek for Missing October Data.

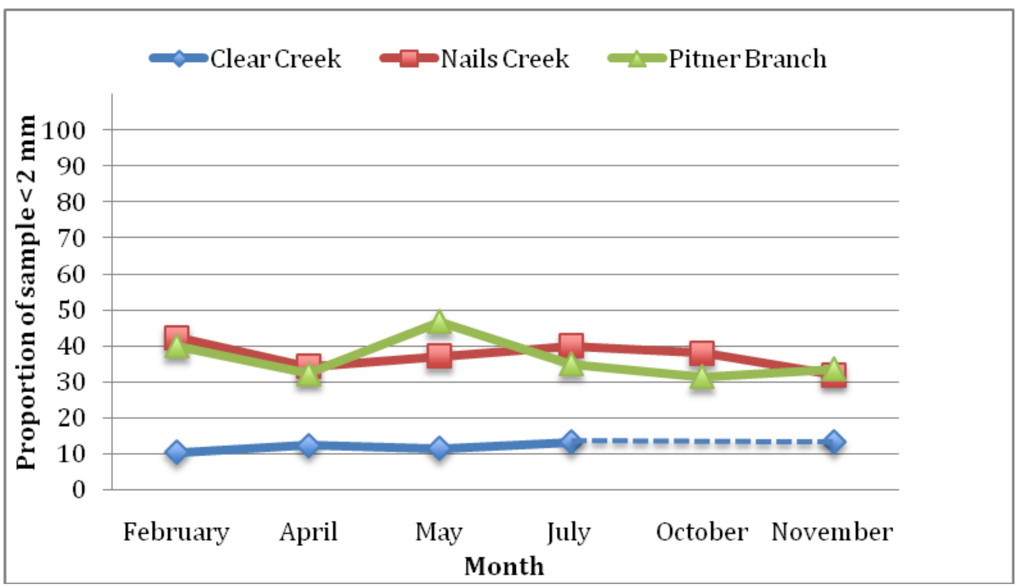

Figure 12. Percent of Sample Less than 2 Mm Values by Month for Data Collected between February 2010 and November 2010. Dashed Line Represents Interpolated Data for Clear Creek for Missing October Data.

CHAPTER FOUR

4 DISCUSSION

4.1 RELATIONSHIPS BETWEEN BED SEDIMENT CHARACTERISTICS AND TMI SCORES

To test hypotheses associated with bed sediment characteristics and TMI scores, I used bivariate correlation. Bivariate correlation analysis of individual substrate metrics to TMI scores did not yield any particularly strong correlations. However, significant ($p < 0.05$) correlations for the metrics %<2mm, D50, and D16 indicate an underlying relationship between substrate and TMI. Although weak, correlations between substrate metrics and TMI scores did generally support alternative hypotheses of the relationships of bed sediment characteristics to TMI.

As hypothesized, D_{50} values showed a positive relationship with TMI scores, indicating that as substrate coarsened, aquatic community assemblages improved. Similarly, results supported the hypothesis that % of particles <2mm had a negative relationship with TMI scores. Surprisingly, no significant correlations existed between visually estimated embeddedness and TMI. Correlation analysis did reveal a negative association between visually estimated embeddedness and TMI ($r = -0.348$); however, the correlation was not significant ($p = 0.059$). I expected to see a decrease in TMI scores with an increase in embeddedness.

Negative relationships between fine sediment, as represented by %<2mm, and TMI scores indicated that, as riffle substrate composition became finer, the condition of macroinvertebrate community assemblages declined. These results generally support those of previous studies, such as those by Angradi (1999), Kaller and Hartman (2004), and Kaller et al. (2001), which used similar benthic macroinvertebrate metrics to quantify macroinvertebrate communities. As in this study, researchers found subtle relationships between fine sediments and benthic macroinvertebrate community metrics. Linking TMI scores or other similar indices directly to substrate can be difficult since many confounding factors exist in complex stream environments. In particular, since macroinvertebrate assemblages are subject to multiple stressors, they can be representative of the overall water quality, and not just of one specific stressor.

4.2 Sediment Characteristics and Benthic Impairment

One-way ANOVA results indicated that quantitatively derived substrate metrics (e.g., D_{50}, D_{16}, and %<2mm) differed significantly among three stream impairment groups—non-impaired, slightly impaired, and moderately impaired—and supported the hypothesis that bed sediment characteristics differ significantly between categories of impairment. However, further analysis, using pairwise t-tests with each substrate metric, revealed that substrate metrics were not able to distinguish between non-impaired and moderately impaired groups. Collapsing the slightly and moderately impaired groups into a single impairment group yielded significant differences between non-impaired and impaired groups, indicating that substrate metrics could detect impairment at a coarse binary scale, but not at the scale at which TMI predicts impairment. This group combination is not arbitrary;

rather, it is based on TDEC criteria. TDEC considers reaches with TMI scores greater than 32 to be non-impaired and those with scores less than 32 to be impaired. Typically, TMI scores are classified into varying levels of impairment, from slightly-impaired to severely impaired. In this study, I combined all groups with a TMI score less than 32 into one single category. Since the dataset contained no scores considered severely impaired, only slightly and moderately impaired groups are present within the combined “impaired” group.

Although these results still generally support the hypothesis that substrate metrics would differ between non-impaired and impaired groups, the ability of quantitatively derived substrate metrics to distinguish between impairment categories at a coarse scale, but inability to distinguish between them at the finer scale at which TMI classifies impairment suggests that these metrics may be useful as a “rough estimate” of conditions within the reach, or perhaps at the level at which a Biorecon would be used, but may not be capable of predicting impairment at the scale necessary for monitoring.

Visually estimated embeddedness could not distinguish between impairment groups when split into non-, moderately, and slightly impaired groups. However, embeddedness was able to distinguish between groups when slightly- and moderately-impaired groups were collapsed into one “impaired” category. Like those of the quantitatively derived substrate metrics, these results suggest that embeddedness may be useful at a coarse scale, but is not capable of predicting impairment at the same level as the TMI.

Univariate logistic regression models, using substrate metrics as explanatory variables for impairment (binary), reported classification rates between 70 and 80%. A logistic regression model using all substrate metrics was developed using a forward stepwise method. The final model retained one explanatory variable, % < 2 mm. The exclusion of other substrate metrics from the model was likely a result of the strong correlation between all of the variables (Table 5). Models consistently predicted impaired sites better than non-impaired sites. Classification rates for impaired sites ranged between 78 and 94% and non-impaired sites ranged between 58 and 67%. This is likely due to the higher number of impaired sites in the dataset. These classification rates are relatively high; however, the addition of more ecoregion reference sites and severely impaired sites would be necessary to make broad-reaching conclusions as to the effectiveness of substrate metrics as a monitoring metric for benthic habitat status.

Results presented here suggest that embeddedness and pebble-count metrics may be useful metrics in coarse monitoring applications where impairment may be obvious, such as those sites where biorecons are performed, but may not be robust enough for applications where the TMI is necessary to determine impairment.

4.3 Visually-Estimated Embeddedness

My personal observations, after performing embeddedness estimates and pebble counts using a modified EMAP protocol at over 30 sites, are that visual metrics can be difficult to estimate in streams dominated by gravels and having few cobbles, and pebble counts may be more consistent in characterizing substrates.

The original use of embeddedness as a metric emerged from studies attempting to quantify fines surrounding biologically relevant substrate for salmonid species in cobble-dominated, western streams (Sylte 2002). Estimating embeddedness in those streams may be easier due to the obvious difference in size classes between cobbles and fines. Sites surveyed for my study were often composed of fine and coarse gravels, and distinguishing between sand and fine gravel proved difficult. Additionally, distinguishing stains on fine gravel, a method commonly used to estimate the proportion of substrate embedded in sands or fines, becomes increasingly difficult on smaller particles. Therefore, it may be more appropriate to use pebble-count metrics in fine-particle beds where embeddedness may be difficult to estimate.

From a habitat perspective, embeddedness may be more biologically relevant in streams that are dominated by coarse particles, such as those in the west where the concept of embeddedness originated, with fines embedding the interstices. Aquatic communities in this type of habitat may be more sensitive to the presence of sands and fines as opposed to those in the Ridge and Valley, where fine-particle beds are relatively common.

Consistently estimating embeddedness between sites can prove difficult. However, strong correlations between embeddedness and other metrics derived from quantitative pebble counts suggest that consistency was maintained throughout this study. Practitioners using this method should ensure that QA/QC standards are maintained to ensure consistency between observers as well as sample sites.

4.4 Fines in Gravel-Dominated riffles

Interstitial sediment collected using the "quoror" method showed no significant relationships with TMI scores; therefore, the null hypothesis, that interstitial sediments are not correlated with TMI scores, could not be rejected. Furthermore, interstitial sediment was not significantly correlated with any bed-sediment metrics.

The lack of significant relationships could result from several factors. The sampling procedure consisted of inserting a 24.5-cm diameter cylinder into the substrate and sampling the slurry created from stirring the substrate. This method was relatively easy in substrates composed of mostly coarse gravel and finer materials; however, the occurrence of cobbles on the surface of the substrate, particularly in the sub-pavement, made it progressively more difficult to obtain a seal on the bottom of the cylinder. When a seal was not obtained and the substrate stirred, the bottom of the cylinder would emit a ribbon of fine sediment downstream and, as a result, a portion of the sample was lost. Similarly, it was also difficult to obtain a seal in streams with relatively flat gravels that were heavily imbricated.

The location of samples within the riffle could potentially produce errors in the data. Samples were taken at three different locations within each riffle. Samples were taken in the thalweg, if present; and, if flow was uniform, samples were taken in the center of the riffle. It is possible that interstitial sediment varies enough in the riffle samples obtained with this approach were not representative of the riffle..

4.5 Variation in Bed Sediment Characteristics Over Time

Results suggest that bed sediment characteristics change little over the course of a year. Both D_{16} and D_{84} showed almost no noticeable variation at all monitoring sites during the year. However, D_{50} did show some variation, even though the proportion of bed particles in the D_{50} particle size class (e.g., fine gravel, coarse gravel) remained constant in the study period. Embeddedness showed some variation throughout the study period, however no consistent pattern emerged from the data. Variance attributed to change with time could be an artifact of variability associated with observer bias. Results generally support the null hypothesis that there is no change over time associated with bed sediment characteristics. However, the lack of change might also reflect the limited number of observations and short study period (1 year). Preliminary observations from this study suggest that substrate sampling could be performed at any time during the year as long flows are low enough to perform surveys. It should be noted that this study focused on inorganic sediment and did not include organic particles such as detritus or woody debris, for which seasonal variation is common (Allan 2004).

4.6 Site Representativeness

Temporal and spatial disjunctions between sites surveyed for this study and site data provided by TDEC could have introduced error into the results. Since it was not possible to have a TDEC biologist accompanying each site visit, it was not possible to know exactly where TDEC sampled. I attempted to select an appropriate riffle using my personal knowledge of macroinvertebrates and knowledge I had gained from accompanying a TDEC biologist in the field to observe methods of site selection. Although I may not have sampled the exact location as TDEC, using GPS coordinates and TDEC location descriptions should have put me close to the TDEC sample area. Also, modifying the EPA EMAP protocol involved concentrating sample transects, usually spread over 40 times the wetted width of the channel, into a detailed analysis of one riffle. Although this method presents a detailed sketch of spatial variability within one riffle, it does not necessarily represent spatial variability of sediments within the reach.

In theory, habitat present in a stream reach is a function of conditions within the upstream contributing area and reach-scale controls. Taking this into consideration, one could argue that if I was in the vicinity of the TDEC collection location (within 1–3 riffles), and as long as there were no significant changes in reach characteristics, contributions by major tributaries, or significant point source inputs of sediment, e.g., storm drainage, that conditions should be similar between areas of benthic macroinvertebrate collections and substrate collections. However, local controls, such as areas of bank erosion or mass wasting, can affect the characteristics of substrate in the immediate vicinity. This type of variability is unavoidable in the field and introduces error into the analysis. To account for local-scale controls and to obtain a representative particle size distribution of a reach, future research should incorporate multiple riffles within the sample reach by spreading transects to include other riffles.

CHAPTER FIVE

5 CONCLUSIONS AND RECOMMENDATIONS

This study proposed to examine relationships between substrate on the channel bed and benthic habitat status (impairment), as determined by TDEC. To accomplish this, a total of 30 sites, corresponding with TDEC monitoring sites, were visited between June 2009 and November 2010. At each site, I characterized bed sediment using visually estimated embeddedness and quantitatively derived metrics (e.g., D_{84}, D_{50}, D_{16}, and % finer than 2 mm). To explore the relationship between interstitial fine sediment and TMI, fine sediments were collected using the "quoror" method. To investigate the variation of inorganic sediment over time, I monitored three sites over the course of a year.

I hypothesized that metrics of fine sediment (embeddedness and %<2mm) were negatively correlated with TMI scores. Visually-estimated embeddedness values were not significantly correlated with TMI scores; thus, I failed to reject the null hypothesis. However, embeddedness data did show a pattern of negative association (r_p= -0.348, p = 0.059) with TMI data, suggesting an underlying relationship between embeddedness and TMI. Furthermore, quantitatively derived %<2mm had a significant negative correlation with TMI scores. Increasing the number of sites may strengthen this relationship.

Embeddedness proved challenging to visually estimate because of the difficulties distinguishing between fine gravels and sand, which are common in streams of the Ridge and Valley. However, strong correlations between visually estimated embeddedness and metrics derived from pebble counts suggest that embeddedness estimates were consistent within sites. Categorizing into degrees of embeddedness (e.g., high, medium, low) or percent ranges (e.g., 0–25%, 25–50%) could potentially reduce the error associated with estimating embeddedness. Additionally, embeddedness may not be biologically relevant to aquatic communities in the fine-particle beds that are relatively common in the Ridge and Valley.

Substrate metrics derived from pebble counts were significantly correlated with TMI scores. Significant positive correlations existed between both D_{50} (r_s= 0.553, p = 0.002) and D_{16} (r_s= 0.546, p = 0.002) with TMI, which supported the alternative hypothesis that median particle diameter would positively corrleate with TMI scores.

Results from one-way ANOVA and Kruskal-Wallace tests indicate that bed sediment characteristics, with the exception of D_{84}, vary significantly. However, pairwise comparisons indicated that substrate metrics alone cannot distinguish between all groups of impairment. Collapsing the two impaired groups (i.e., slightly impaired, moderately impaired) yielded significant differences in substrate metrics between non-impaired and impaired groups, and support the alternative hypothesis that substrate metrics vary significantly between groups.

I used univariate logistic regression models to test the predictive capability of substrate metrics on stream impairment status. With the exception of D_{84}, all logistic regression models were signficant and classification rates were 58–67%. This supported the alternative hypothesis that logistic regression models would be able to predict impairment based on substrate metrics. Before broad-reaching conclusions can be made about the effectiveness of substrate metrics as predictors of impairment based on logistic regression, severely impaired sites and additional ecoregion reference sites need to be added to the dataset.

Both visually estimated embeddedness and quantitatively derived substrate metrics were capable of distinguishing between groups of impairment with relatively high classification rates. However, the lack of significant correlations between embeddedness and raw TMI scores suggest that the use of quantitatively derived substrate metrics may be a more robust approach to predicting benthic impairment. Furthermore, the inability of any substrate metrics to differentiate between varying degrees of impairment suggests that single substrate metrics may be useful as a rough estimate of condition, but that they are not capable of predicting impairment at the level of a SQSH survey and resulting TMI score.

I expected to see a negative correlation between the concentration of interstitial fine sediments, collected using the "quoror" method, and TMI scores.

Interstitial fine sediment was not significantly correlated with TMI scores. The lack of association could be a result of spatial variability of fine sediments within the channel and difficulty obtaining a respresentative sample, or of the difficulty of obtaining a proper seal on the sampler, which led to losses in fine sediments downstream.

Little variation in bed sediment was observed while monitoring three sites over the course of a year. The lack of variation suggests that substrate sampling can be performed at any time of the year. However, it should be noted that this study focused on inorganic sediment particles and not on organic particles.

In summary, this thesis demonstrated that pertinent relationships between substrate metrics and TMI scores do exist and that substrate metrics show potential for monitoring stream impairment with respect to sediment. The lack of significant differences between varying classes of reach impairment suggest that substrate metrics may not be able to distinguish impairment at the level necessary for monitoring impairment. However, substrate metrics may be of potential use in monitoring sites where impairment is less ambiguous. The lack of seasonal influence on substrate characteristics suggests that seasonal restrictions on substrate surveys are unneccessary.

Future research should add severely impaired sites to the dataset and increase the number of ecoregion reference sites. Future studies may also consider spreading transects over multiple riffles within the same reach, as opposed to concentrating all transects within one riffle as this study did. This may provide a more representative characterization of the stream reach. Additionally, observer bias and variability among observers would have to be addressed in order to fully assess the functionality of visually estimated embeddedness as a monitoring tool.

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APPENDICES

Appendix 1. Field Data Sheet Used for Substrate Characterization.

Site ID: **Date:** **Recorder:**
T-Interval: **Time(start/end):** **Surveyer:**

Transect	Width (m)		0%	25%	50%	75%	100%	Comments
1	Wetted: Interval: Tape:	Dist LB (m) Depth (cm) Embedd. (%) Size Class Code						
2	Wetted: Interval: Tape:	Dist LB (m) Depth (cm) Size Class Code						
3	Wetted: Interval: Tape:	Dist LB (m) Depth (cm) Embedd. (%) Size Class Code						
4	Wetted: Interval: Tape:	Dist LB (m) Depth (cm) Size Class Code						
5	Wetted: Interval: Tape:	Dist LB (m) Depth (cm) Embedd. (%) Size Class Code						
6	Wetted: Interval: Tape:	Dist LB (m) Depth (cm) Size Class Code						
7	Wetted: Interval: Tape:	Dist LB (m) Depth (cm) Embedd. (%) Size Class Code						
8	Wetted: Interval: Tape:	Dist LB (m) Depth (cm) Size Class Code						
9	Wetted: Interval: Tape:	Dist LB (m) Depth (cm) Embedd. (%) Size Class Code						
10	Wetted: Interval: Tape:	Dist LB (m) Depth (cm) Size Class Code						
11	Wetted: Interval: Tape:	Dist LB (m) Depth (cm) Embedd. (%) Size Class Code						
12	Wetted: Interval: Tape:	Dist LB (m) Depth (cm) Size Class Code						

Slope	Riffle Length	Upstream	Downstream	Comments
		Water Depth:	Water:	
		Stadia Rod:	Stadia Rod:	

Water/Weather/Riparian Conditions:

Site ID:

Transect	**Width (m)**		**0%**	**25%**	**50%**	**75%**	**100%**	**Comments**
13	Wetted:	Dist LB (m)						
	Interval:	Depth (cm)						
	Tape:	Embedd. (%)						
		Size Class Code						
14	Wetted:	Dist LB (m)						
	Interval:	Depth (cm)						
	Tape:	Size Class Code						
15	Wetted:	Dist LB (m)						
	Interval:	Depth (cm)						
	Tape:	Embedd. (%)						
		Size Class Code						
16	Wetted:	Dist LB (m)						
	Interval:	Depth (cm)						
	Tape:	Size Class Code						
17	Wetted:	Dist LB (m)						
	Interval:	Depth (cm)						
	Tape:	Embedd. (%)						
		Size Class Code						
18	Wetted:	Dist LB (m)						
	Interval:	Depth (cm)						
	Tape:	Size Class Code						
19	Wetted:	Dist LB (m)						
	Interval:	Depth (cm)						
	Tape:	Embedd. (%)						
		Size Class Code						
20	Wetted:	Dist LB (m)						
	Interval:	Depth (cm)						
	Tape:	Size Class Code						
21	Wetted:	Dist LB (m)						
	Interval:	Depth (cm)						
	Tape:	Embedd. (%)						
		Size Class Code						

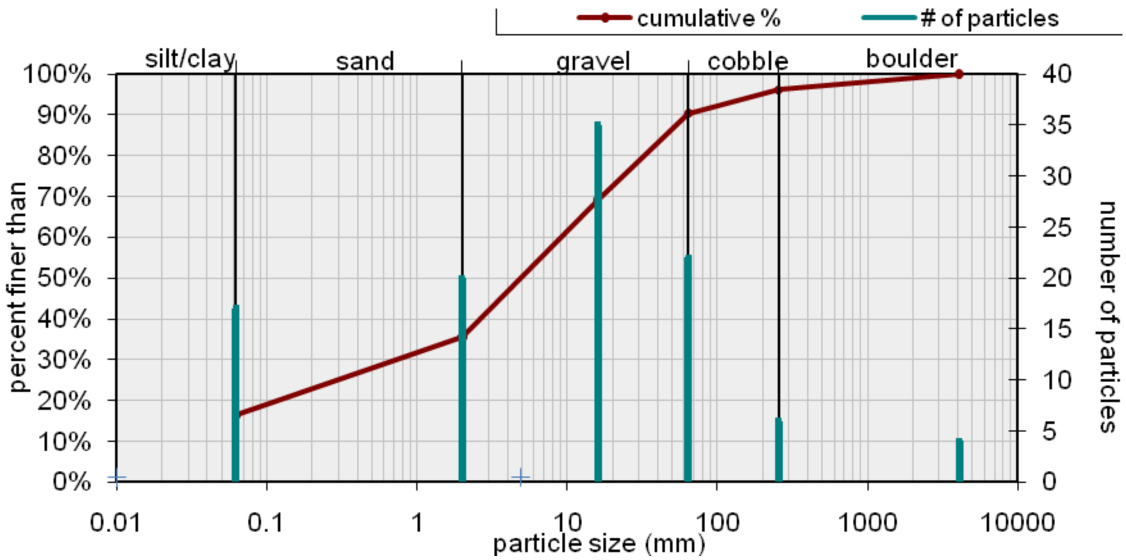
Quoror

Water	**Head**	**Mid**	**Tail**			
1						
2						
3						
4						
5						
Post						

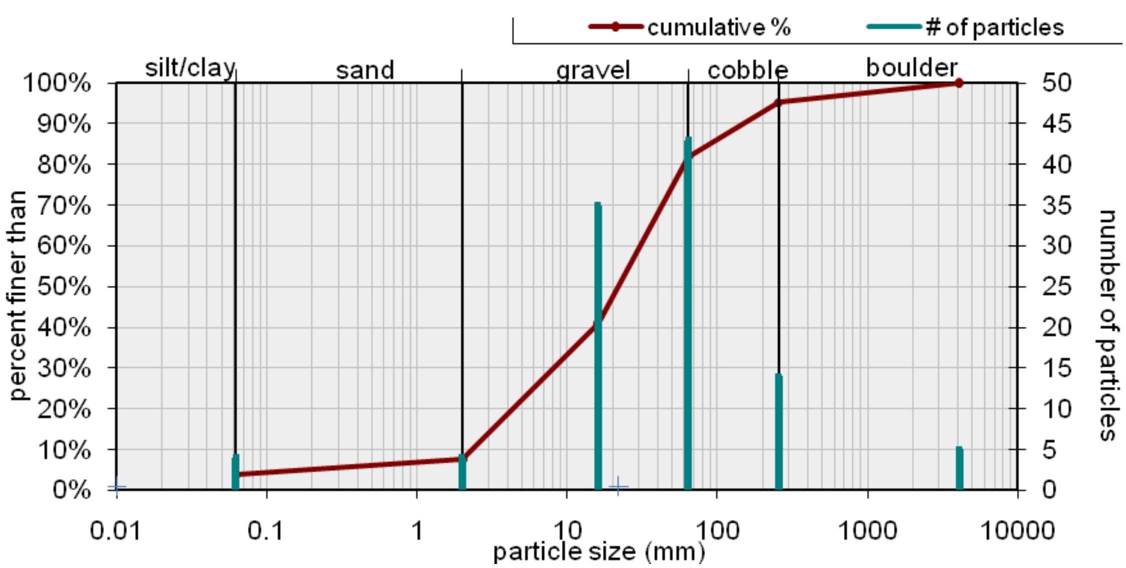
Substrate Size Class	**Embedd. (%)**
RR = Bedrock (Rough) - (Larger than a car)	0
BL = Boulder (250-4000 mm) - (Basketball to car)	
CB = Cobble (64 to 250 mm) - (Tennis Ball to Basketball)	
GC = Coarse Gravel (16 to 64 mm) - (Marble to Tennis Ball)	
GF = Fine Gravel (2-16 mm) - (Ladybug to Marble)	
SA = Sand (.06 to 2 mm) - (Gritty- up to Ladybug size)	100
FN = Silt/Clay/Muck- (Not Gritty)	100
HP = Hardpan - (Firm consolidated fine substrate	0
WD = Wood - Any Size	
***CX* - Comment, see comment field**	

Appendix 2. Particle Size Distribution Curves for Study Sites

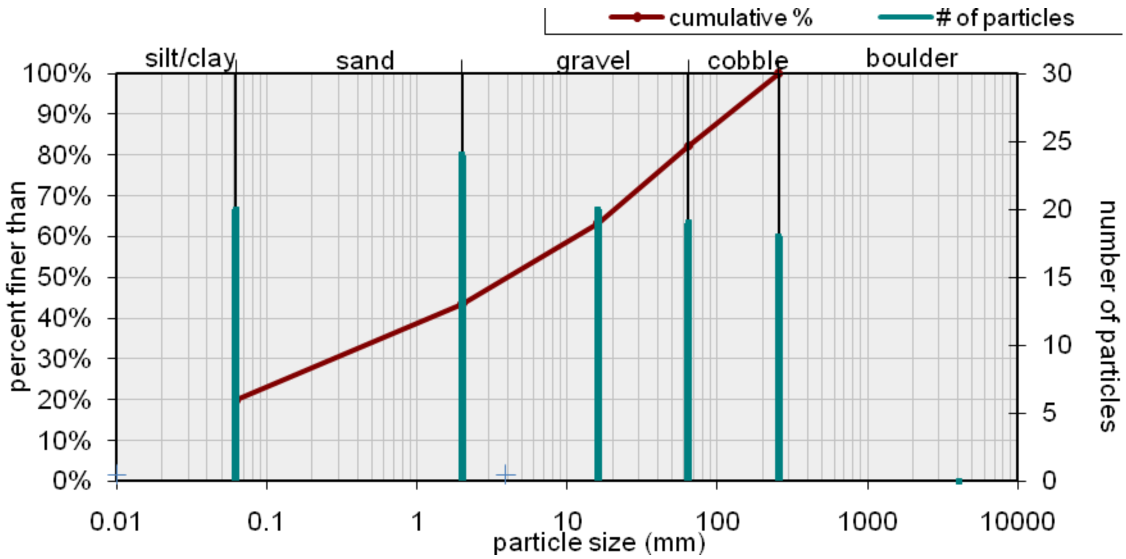
Particle size distribution of BUFFA001.1AN



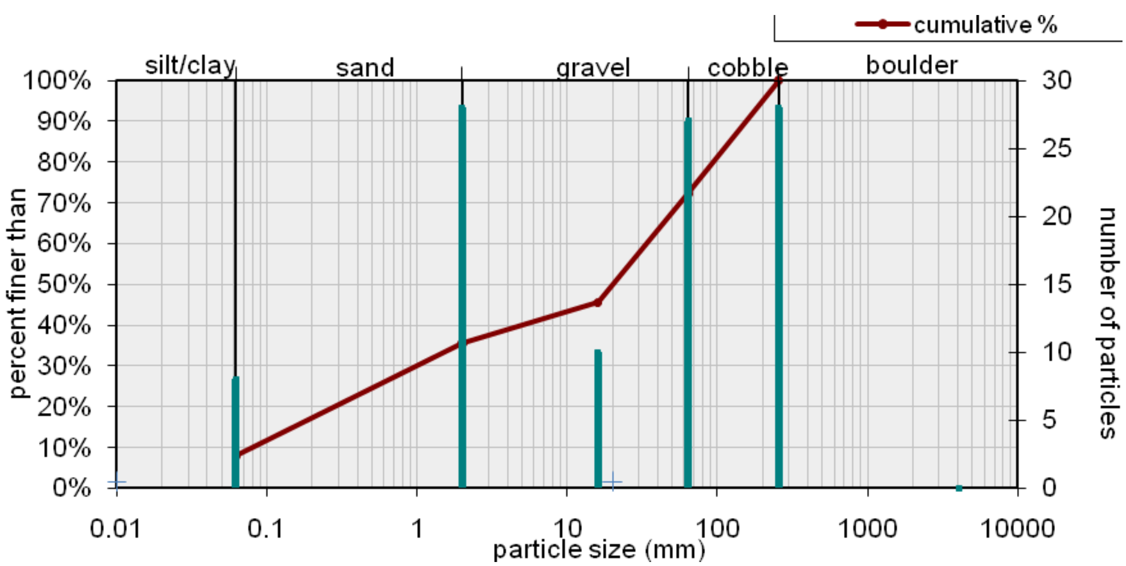
Particle size distribution of BULLRU32.2UN



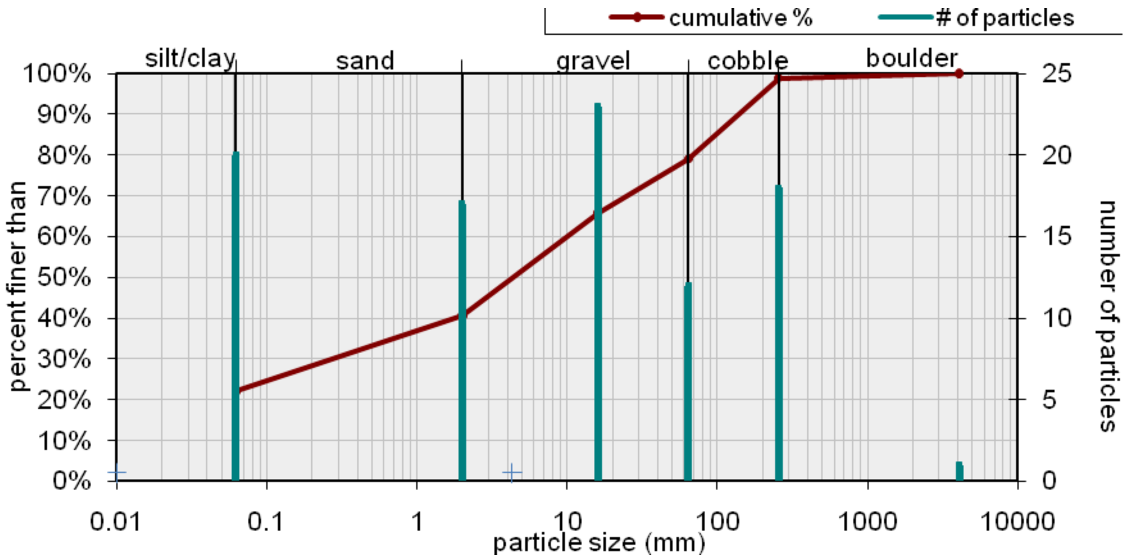
Particle size distribution of BULLR1T0.6UN



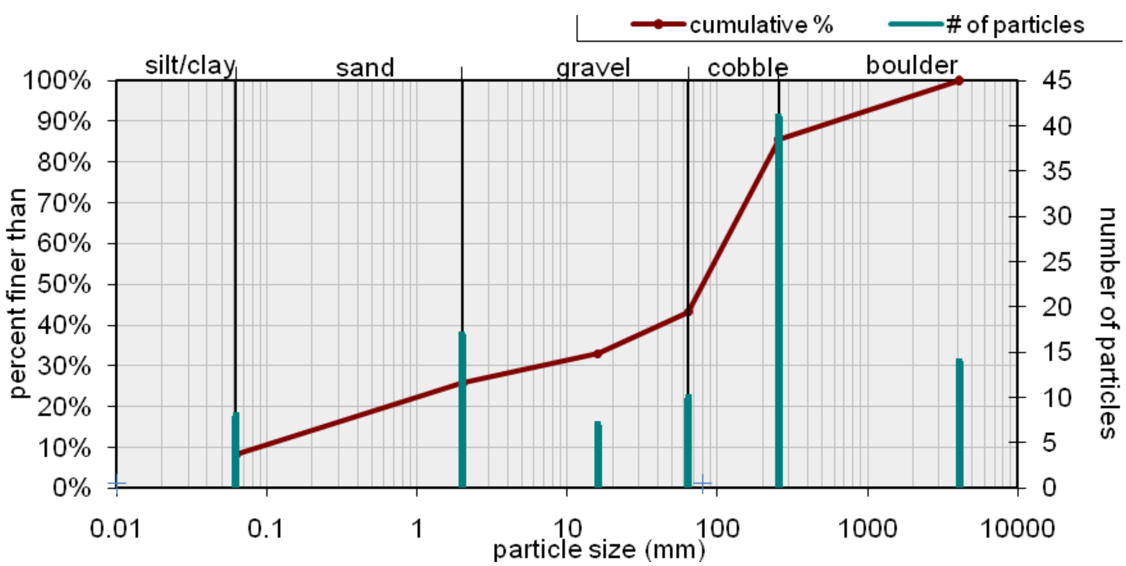
Particle size distribution of CARTE000.1SE



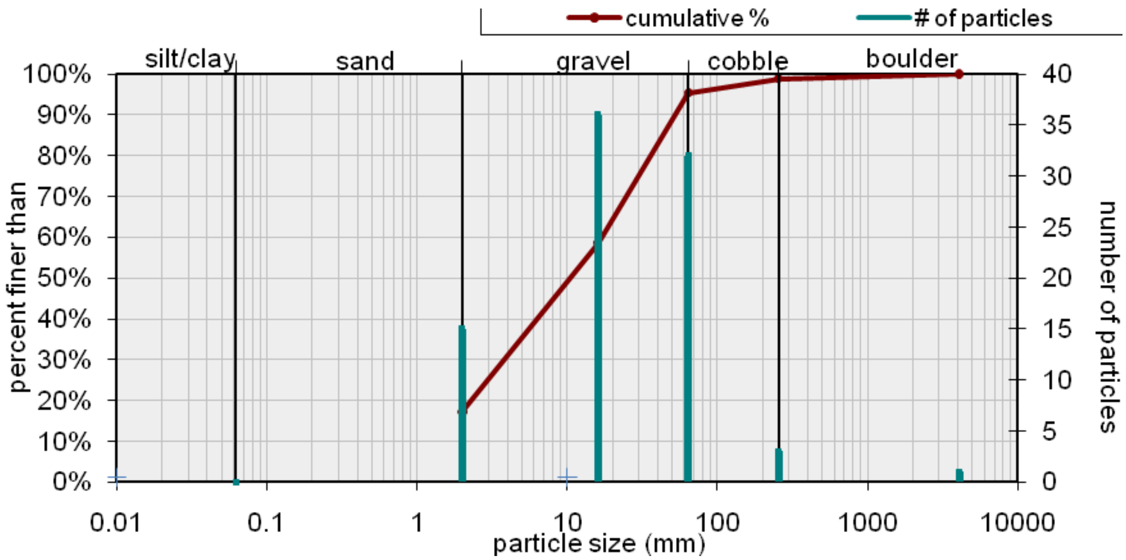
Particle size distribution of COX000.2KN



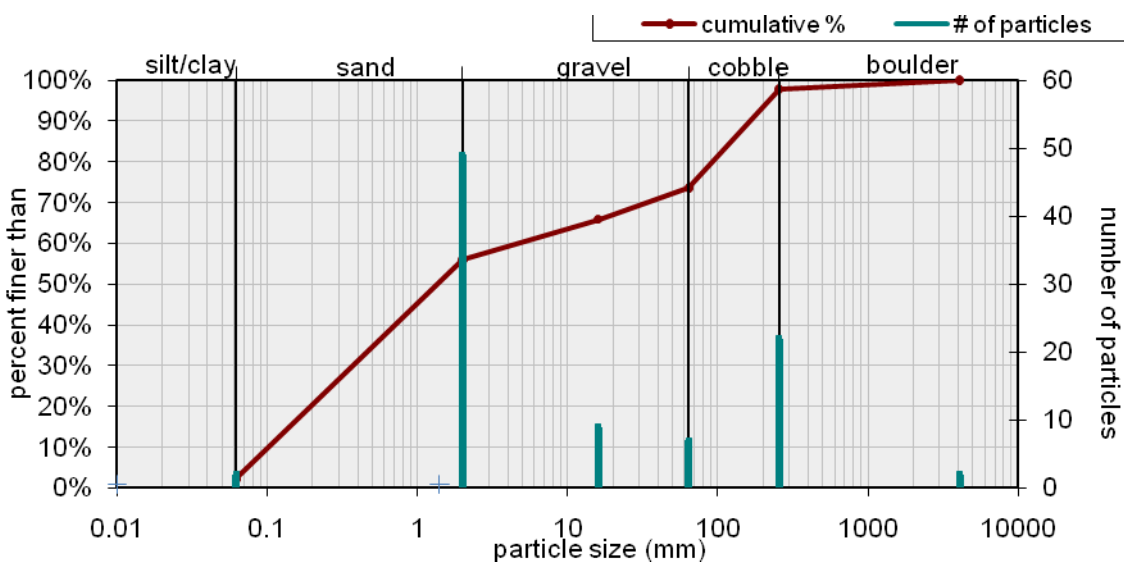
Particle size distribution of CROOK007.2BT



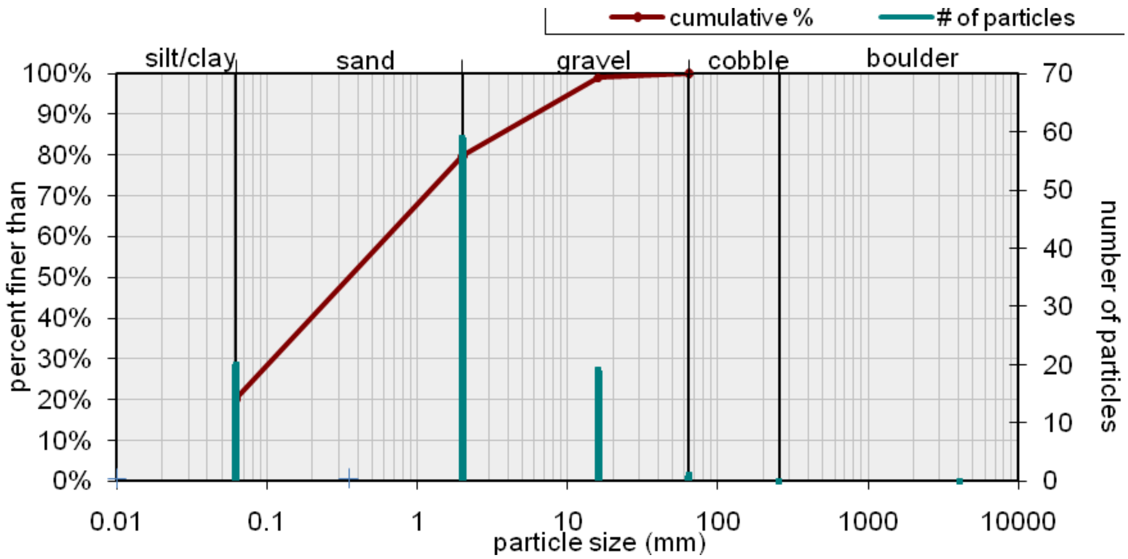
Particle size distribution of ECO67F06 (Clear Creek)



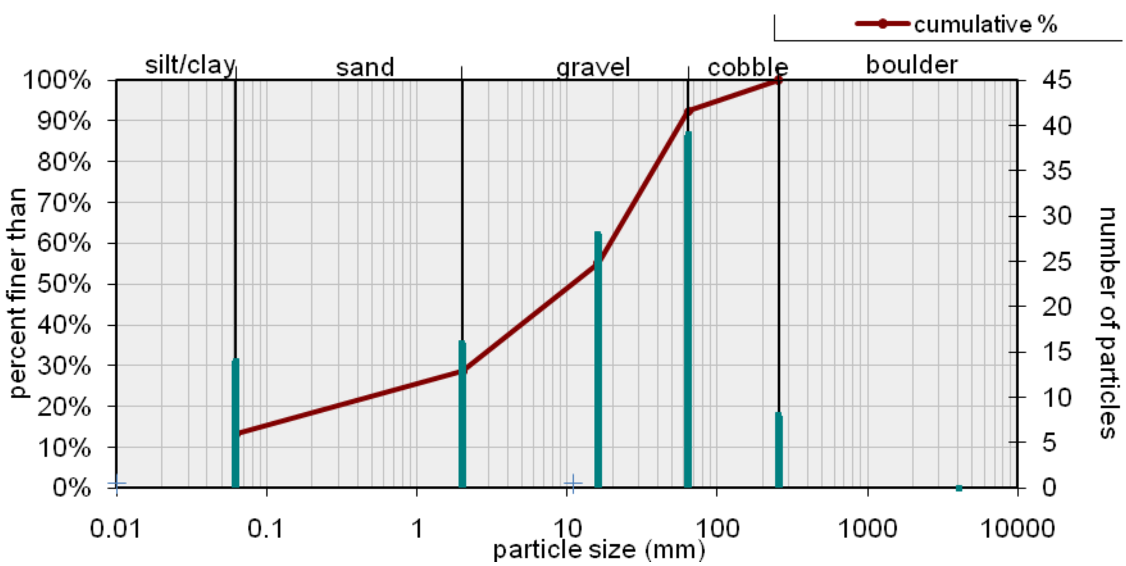
Particle size distribution of ELLEJ000.1BT



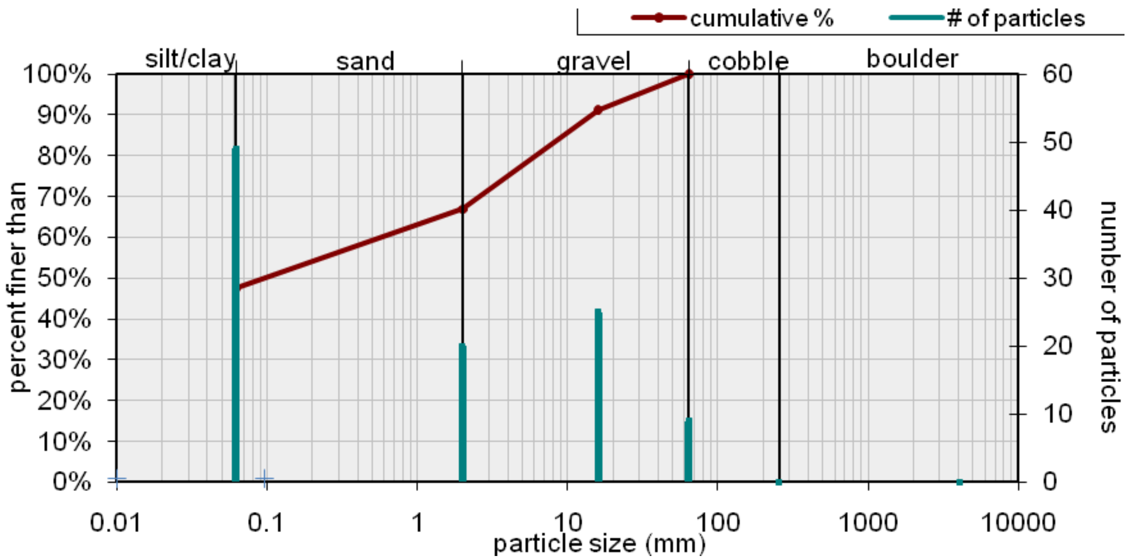
Particle size distribution of ELLEJ008.0BT



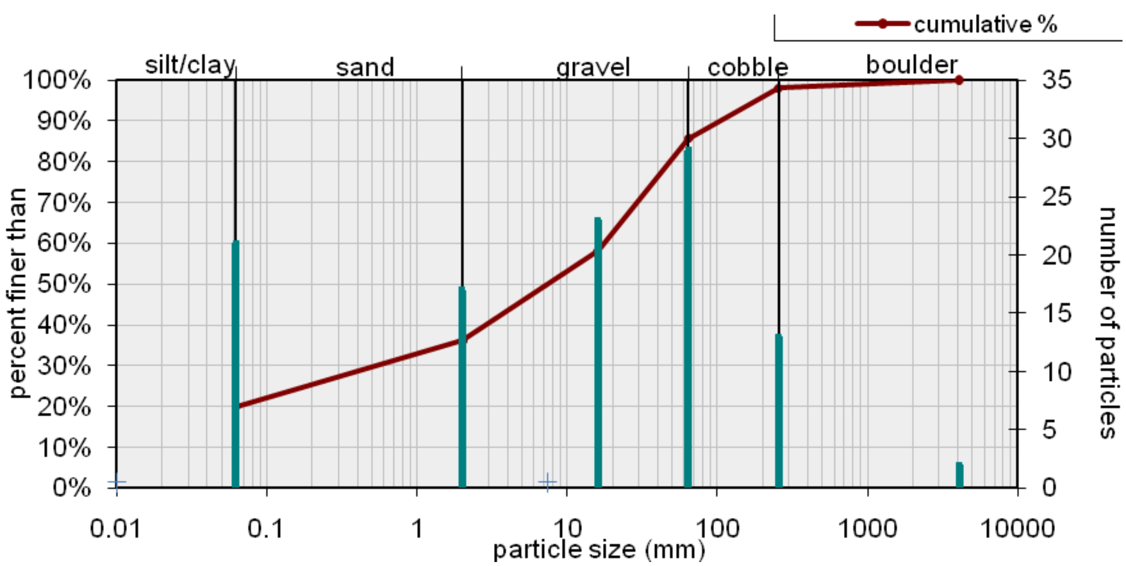
Particle size distribution of FECO67I12 (Mill Branch)



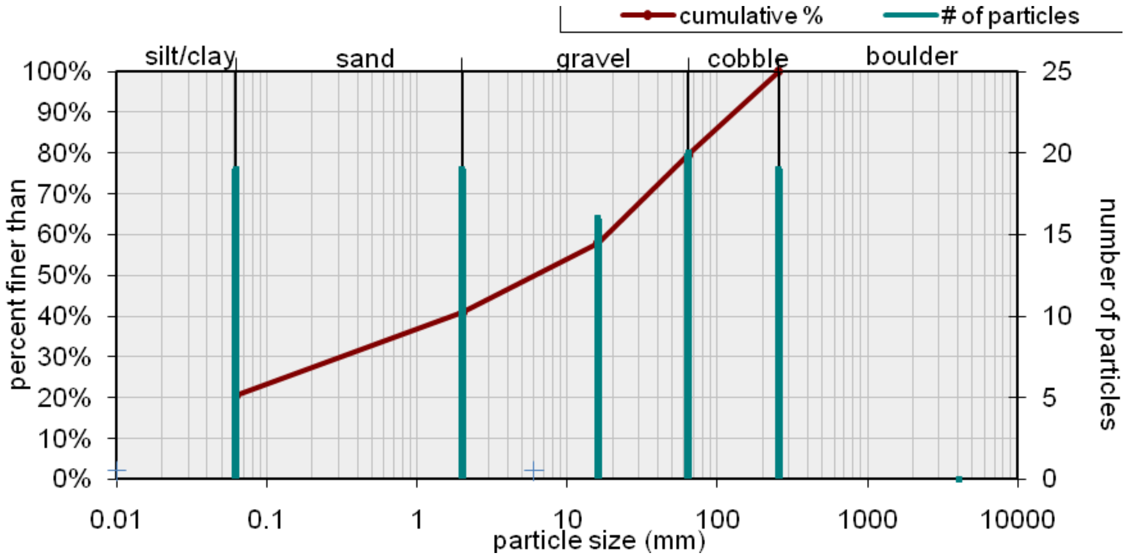
Particle size distribution of FLAG000.1BT



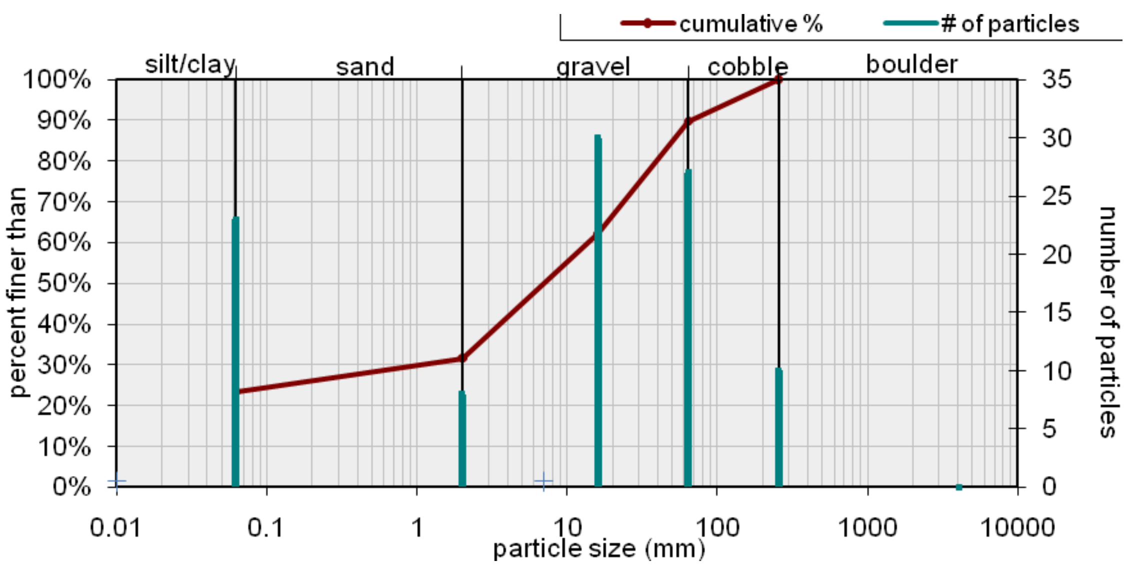
Particle size distribution of HINDS006.8AN



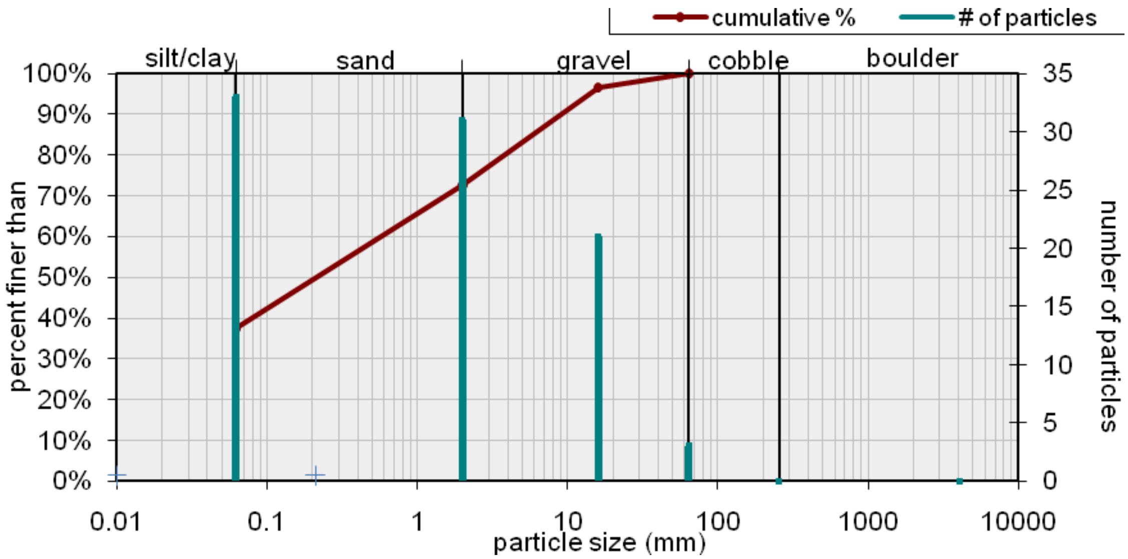
Particle size distribution of HINDS014.1AN



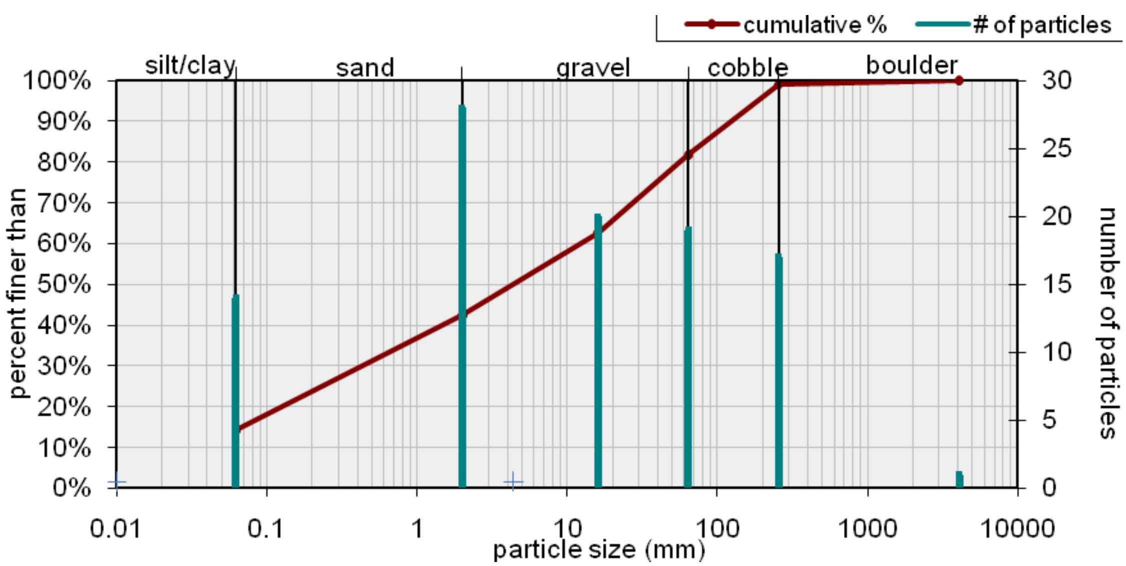
Particle size distribution of HOLLY000.5BT



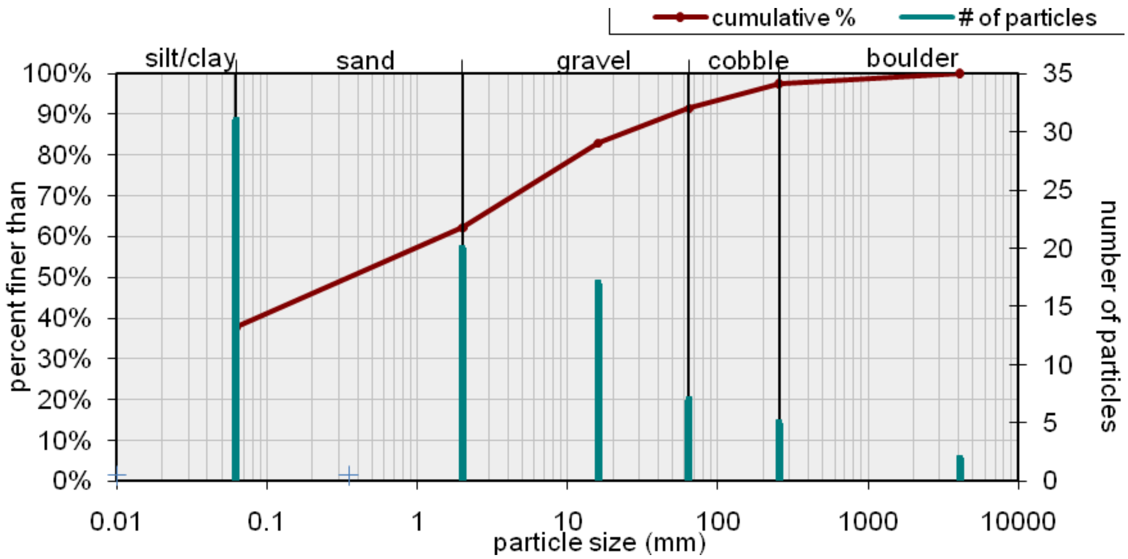
Particle size distribution of LELLE000.2BT



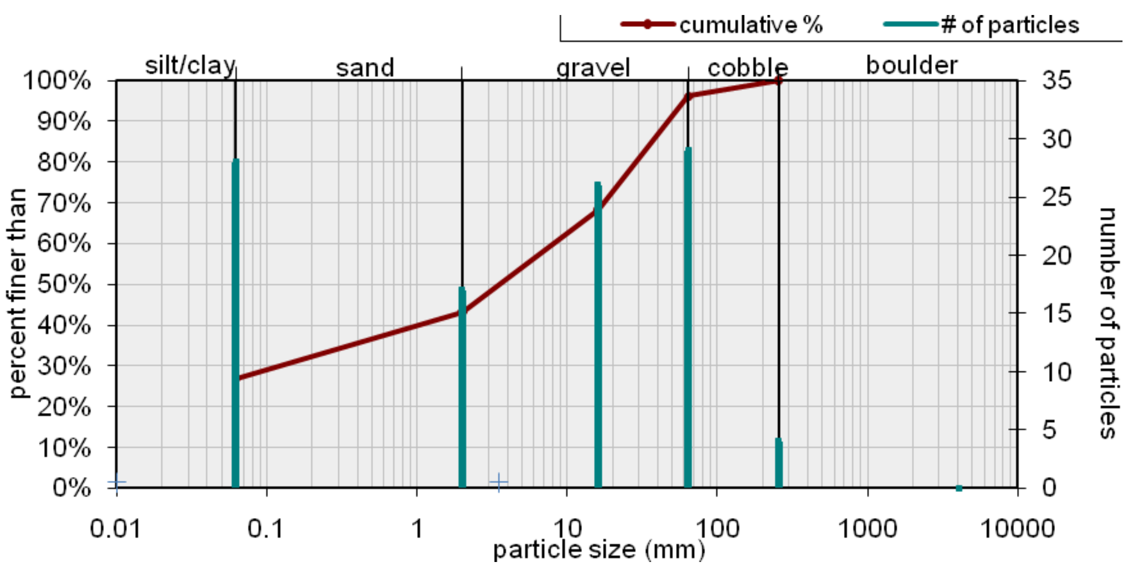
Particle size distribution of LTURK001.4KN



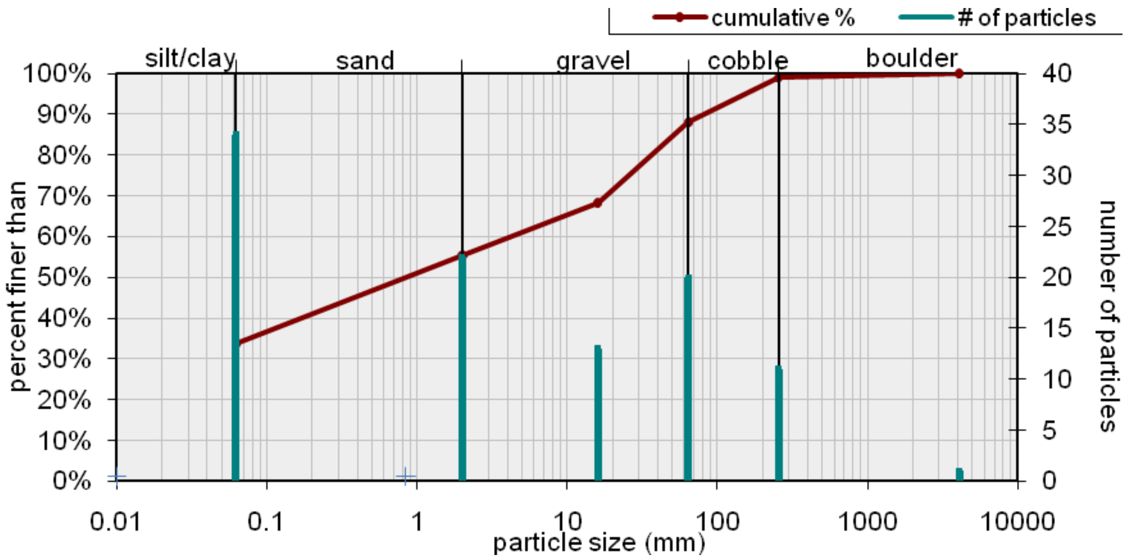
Particle size distribution of MCCAL000.9KN



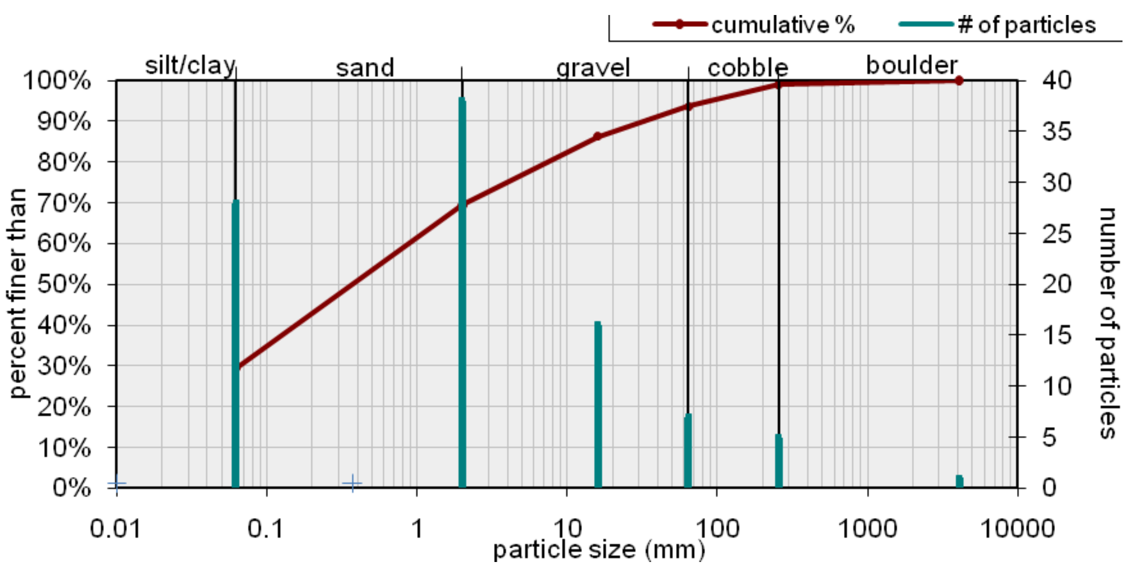
Particle size distribution of NAILS000.7BT



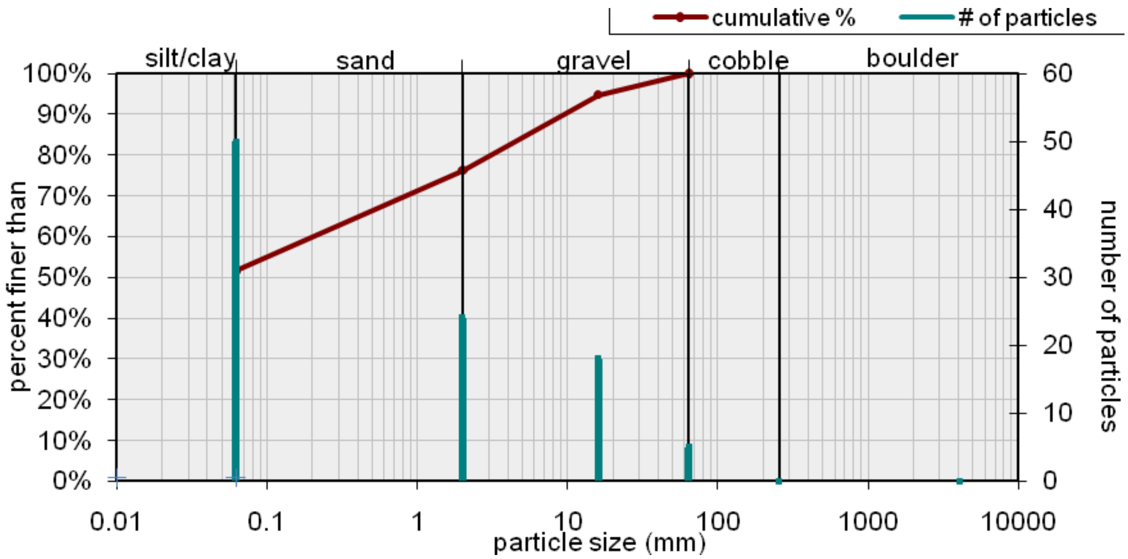
Particle size distribution of NAILS004.5BT



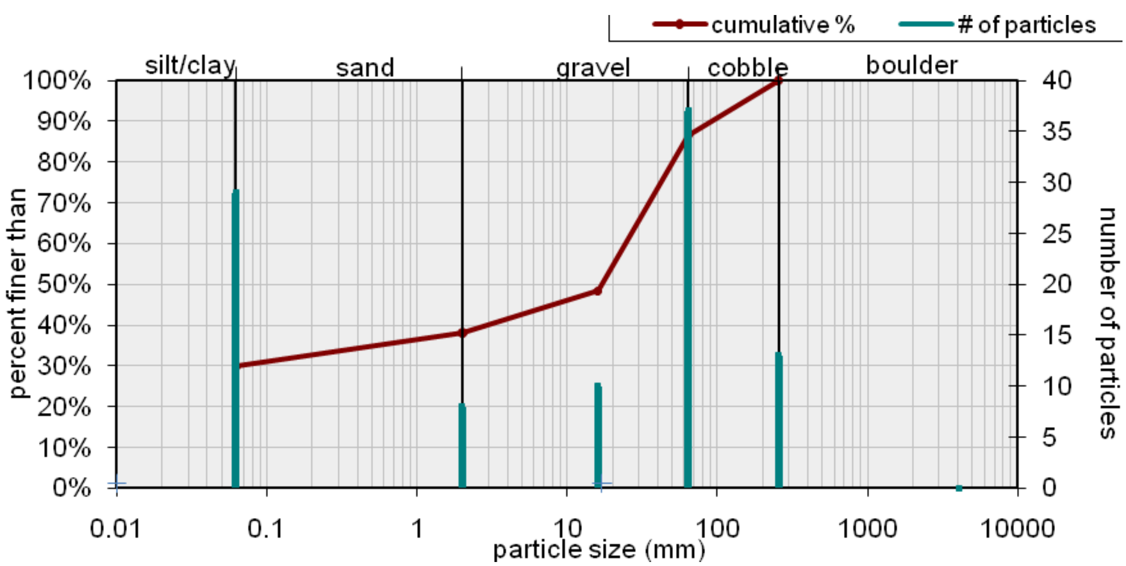
Particle size distribution of NAILS008.3BT



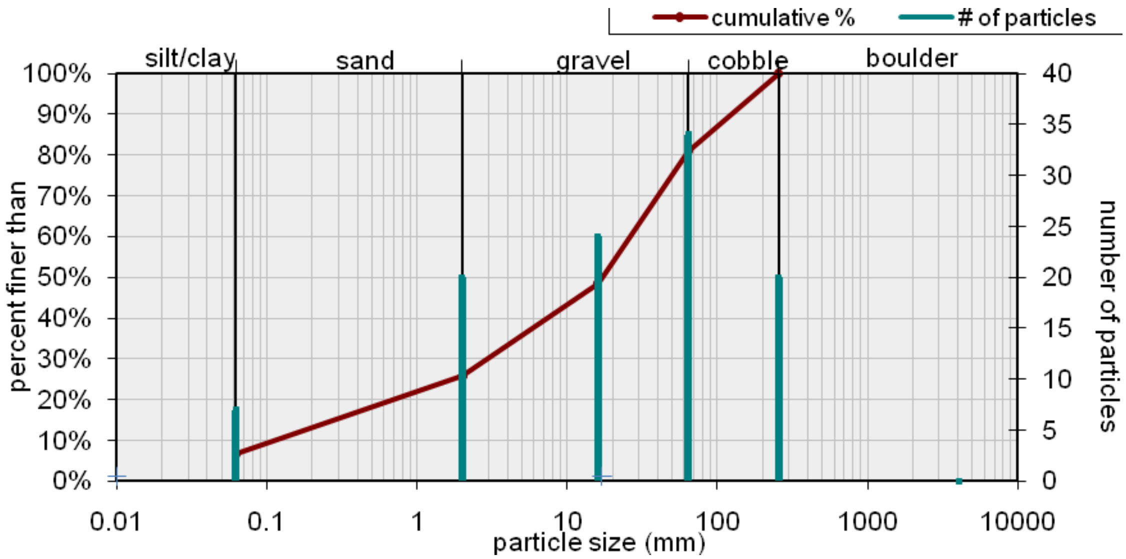
Particle size distribution of PEPPE000.7BT



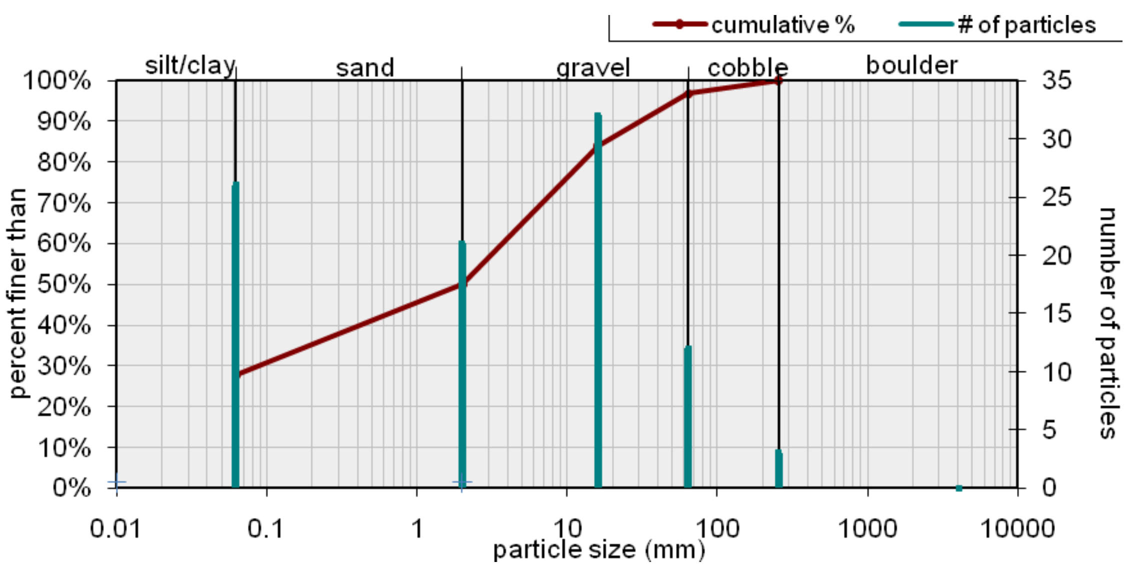
Particle size distribution of PITNE000.8BT



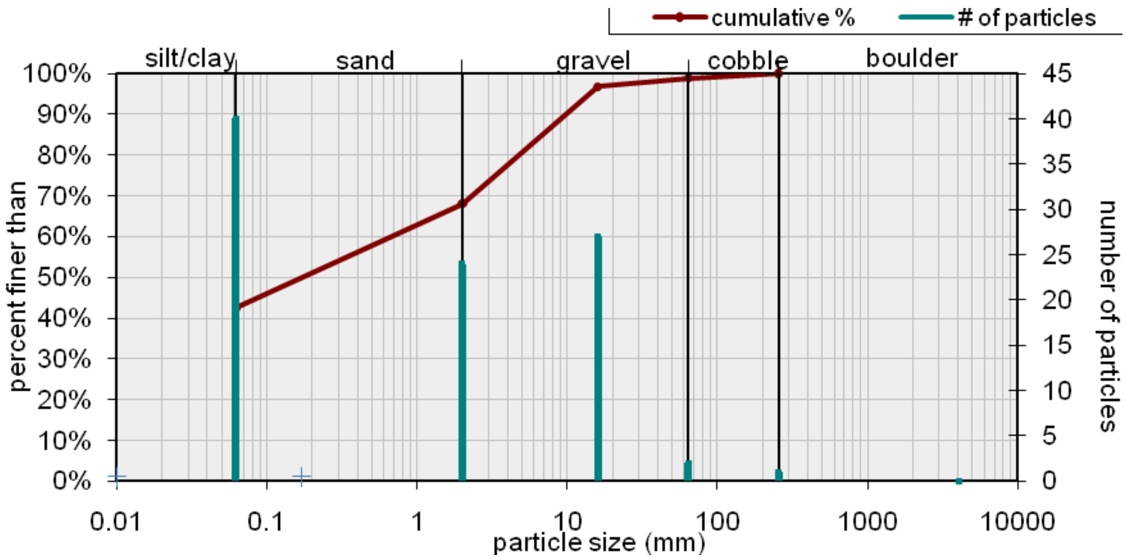
Particle size distribution of PROCK003.1RO



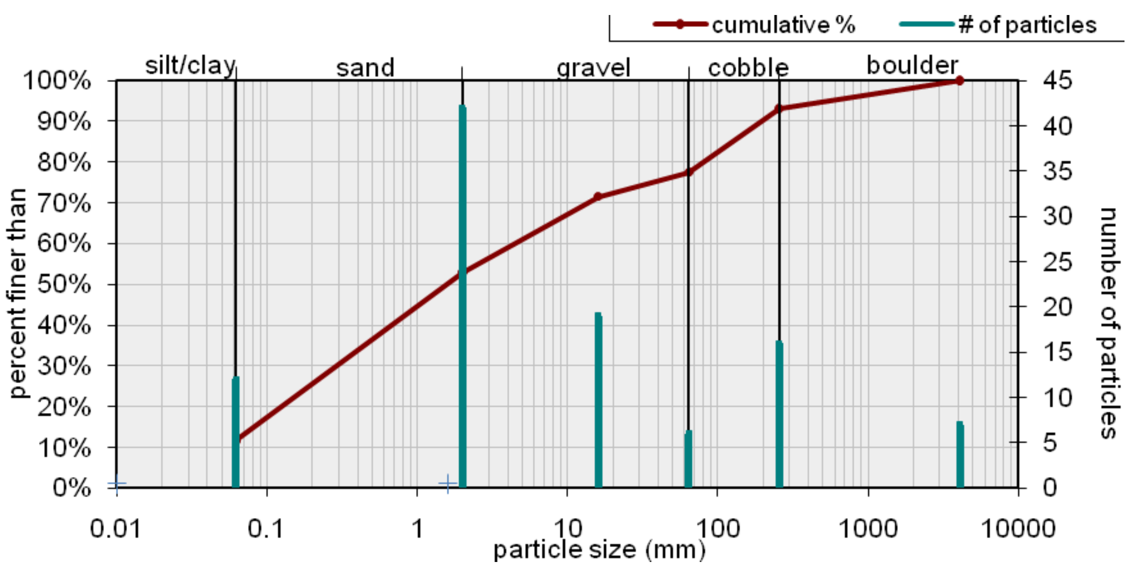
Particle size distribution of ROCKY000.8BT



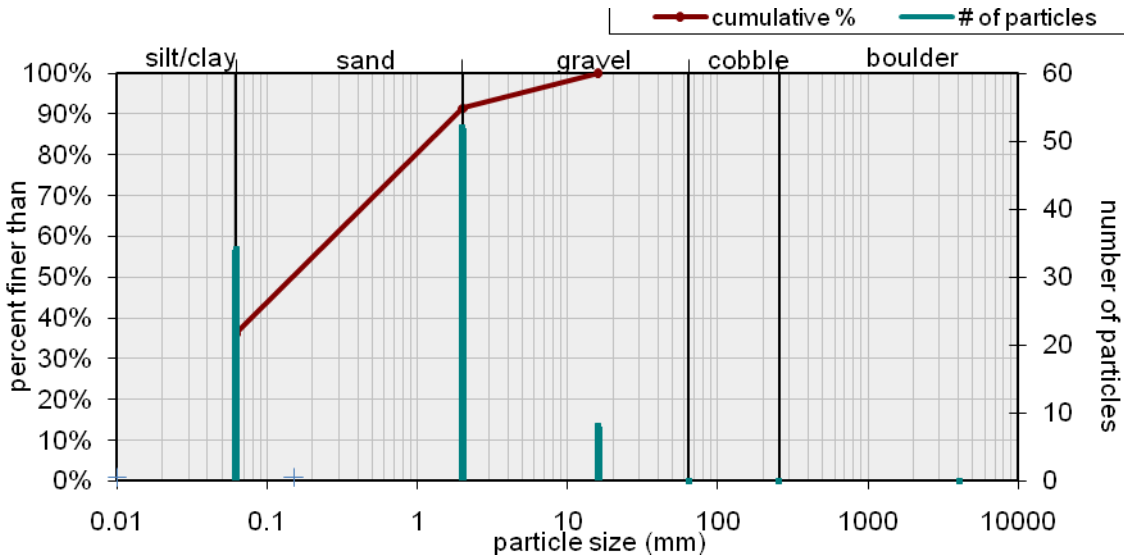
Particle size distribution of RODDY000.8BT



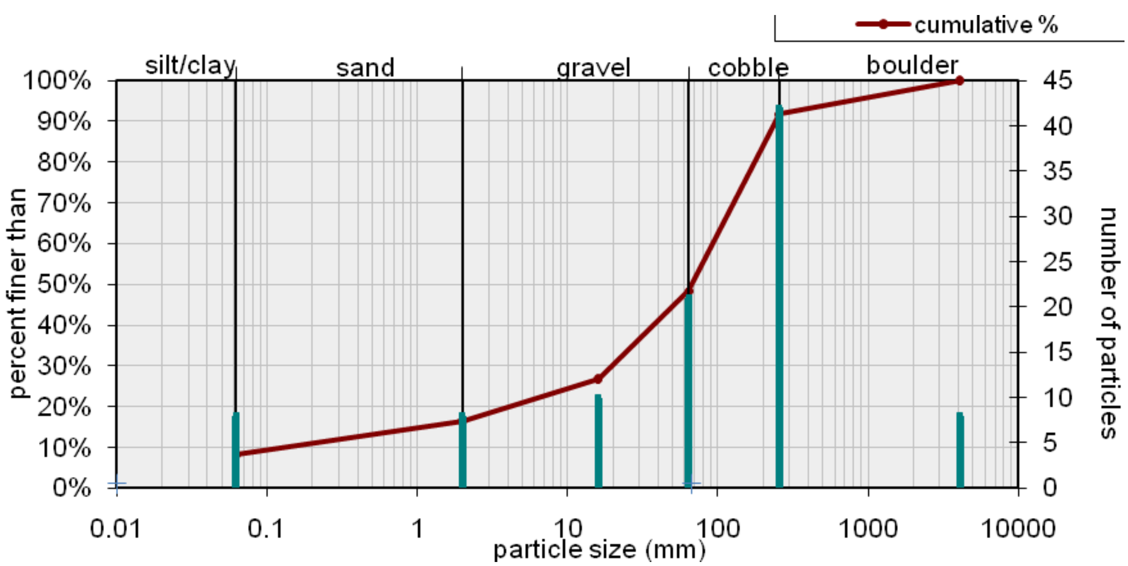
Particle size distribution of RUSSE000.9BT



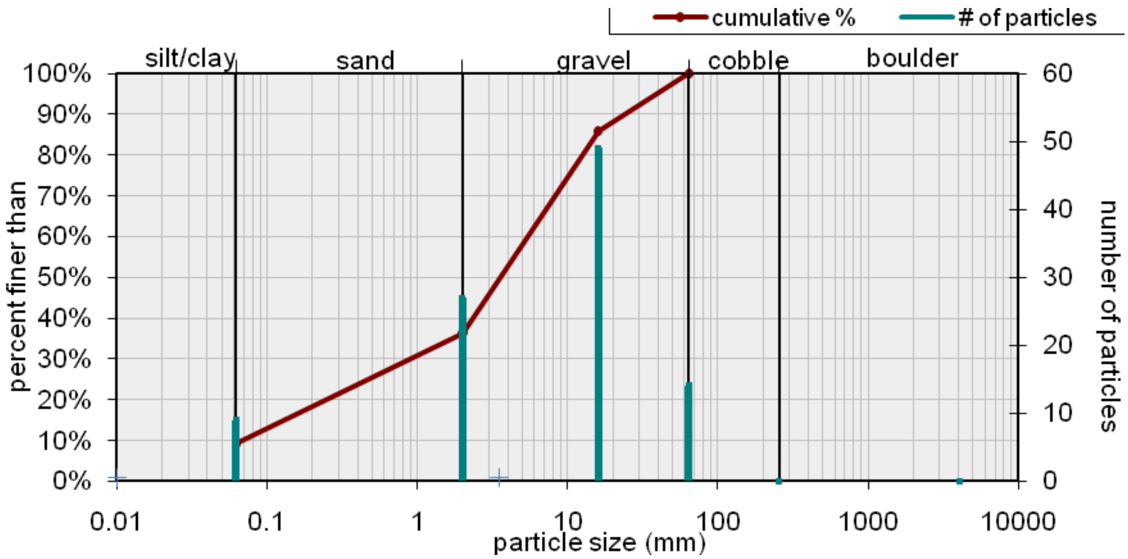
Particle size distribution of SFCRO001.0BT



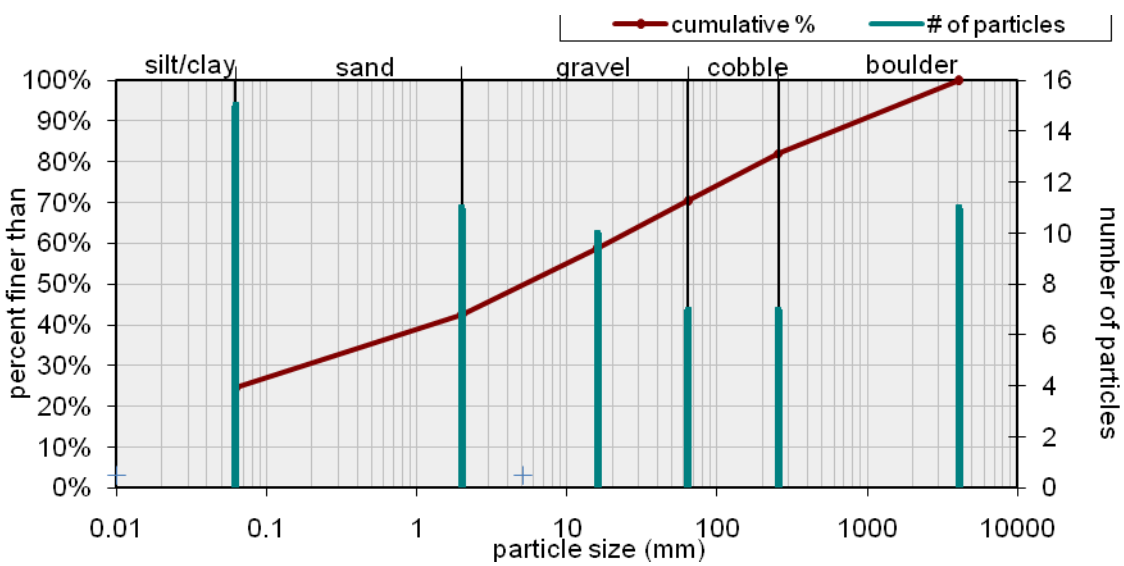
Particle size distribution of STOCK003.2KN



Particle size distribution of STOCK005.3KN



Particle size distribution of WILDW000.1BT



VITA

James Hunter Terrell was raised in Brentwood, Tennessee. His love of running water began as a young child on fishing trips with his father and grew through high school while exploring the Harpeth River. Hunter received his B.A. in Environmental Studies with a minor in Wildlife and Fisheries Science from the University of Tennessee in the Fall of 2004. Before beginning the Master's program in the Department of Geography in 2009, Hunter contracted with the Tennessee Valley Authority's Natural Heritage program, which gave him the opportunity to explore the Tennessee Valley. During graduate school, Hunter was fortunate enough to explore the streams of East Tennessee and join Dr. Carol Harden and James Hartsig for fieldwork in the paramo grasslands of Ecuador. Upon graduation, Hunter hopes to continue to gain experience in water quality and biological monitoring as well as natural resource management.